

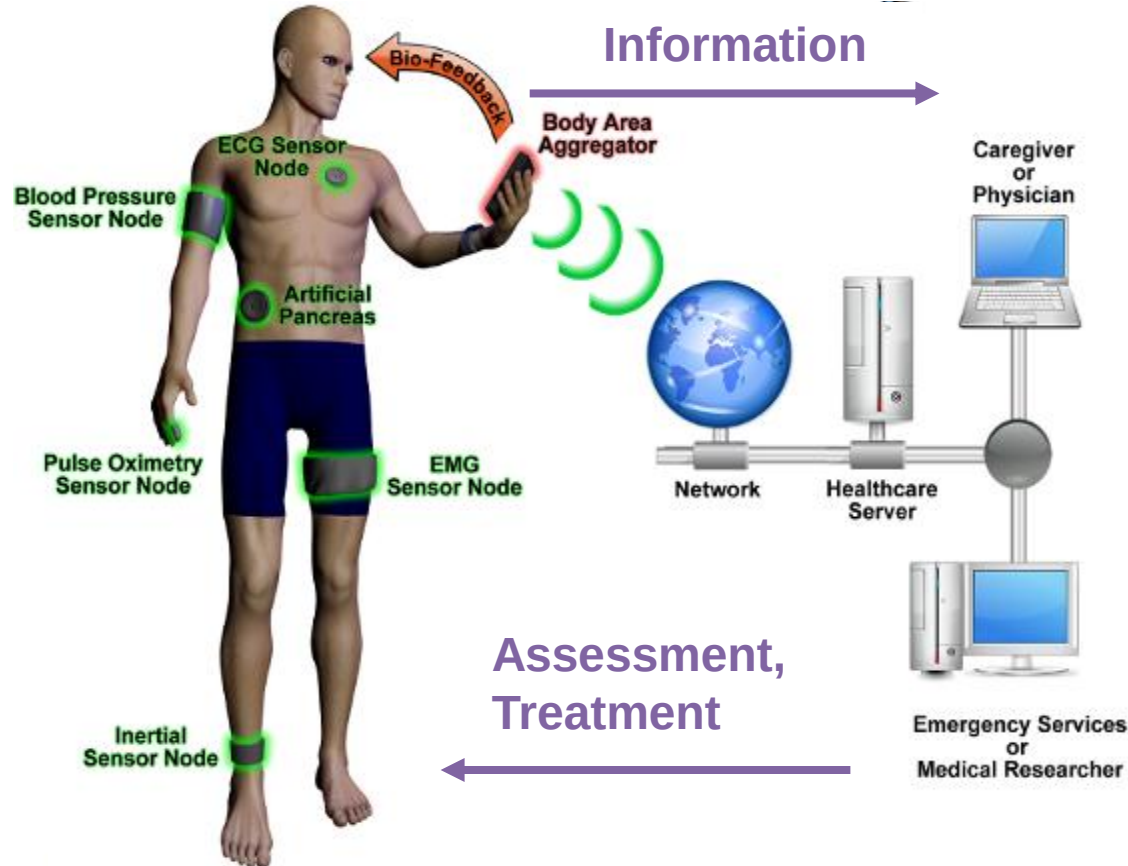
A Batteryless 19 μ W MICS/ISM-Band Energy Harvesting Body Area Sensor Node SoC

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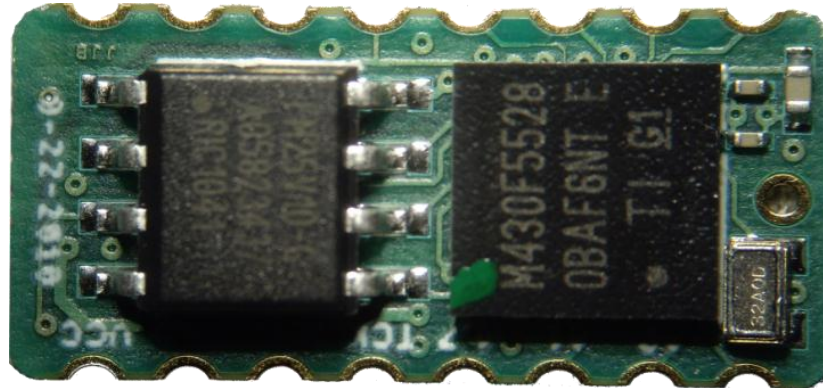
Introduction



- Wireless body area sensor nodes (BASN) enable inexpensive continuous monitoring of patients
- Battery replacement for body-worn devices may not be feasible or desirable

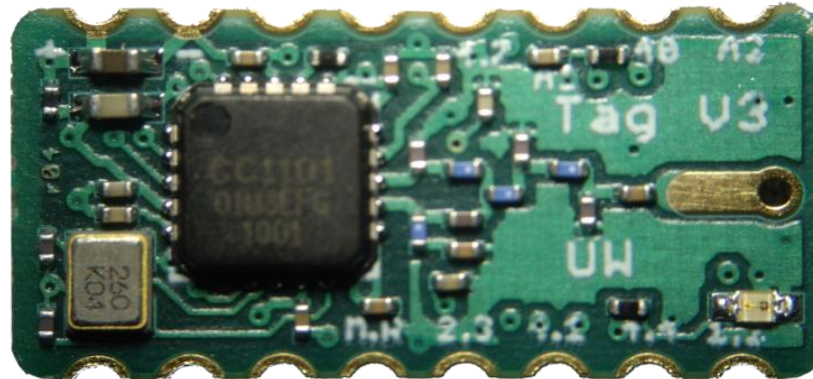
Commercial-off-the-shelf (COTS) wireless BASN

(top)
Digital Logic
Memory



- Memory
- Microcontroller
- Watch Crystal

(bottom)
Radio



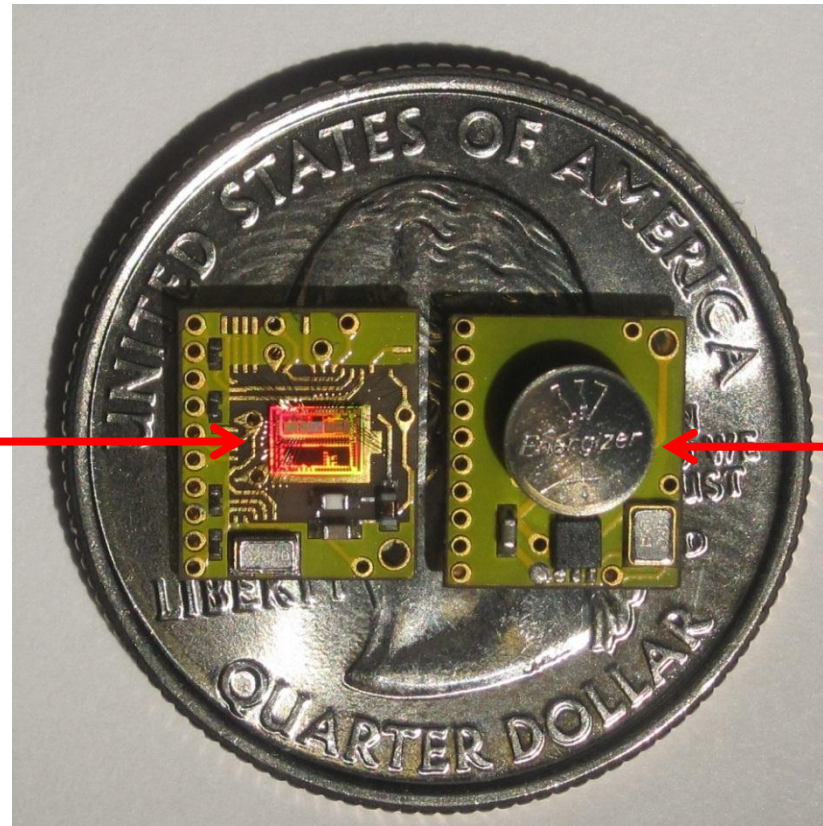
- RF Transceiver
- Matching network
- RF crystal
- Antenna connector

Other Components: Amplifiers, ADC, Power, Interface

- $P_{AVG} > 20 \text{ mW}$ (continuous transmission)
 $< 2 \text{ hours}$ of battery life (33mAh)

Custom low-power BASN IC

Custom IC

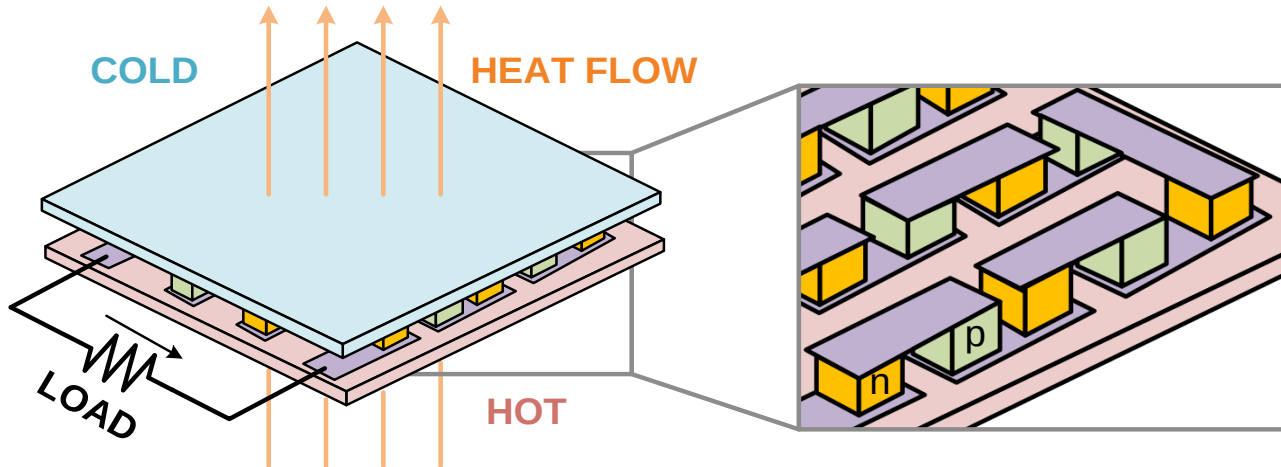


Battery
(33 mAh)

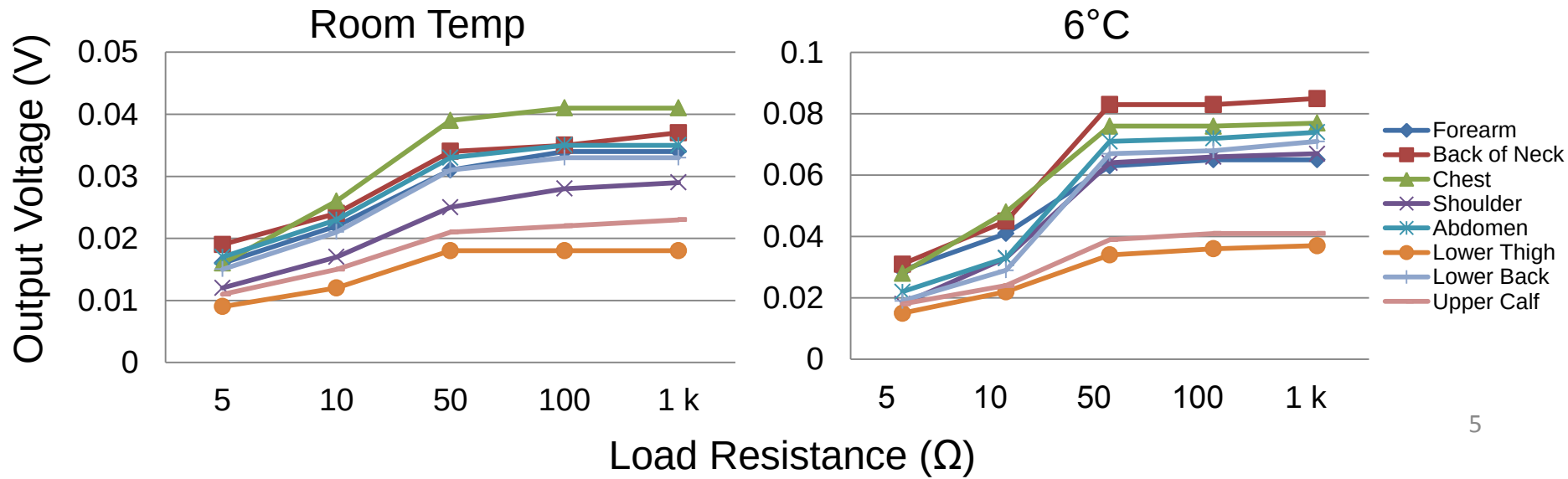
Rai, ISSCC 2009. Morrison, DAC 2010

- Digitize & transmit ECG, EMG, neural data
- No signal processing
- Battery life: 3 days (100% duty cycle (DC))

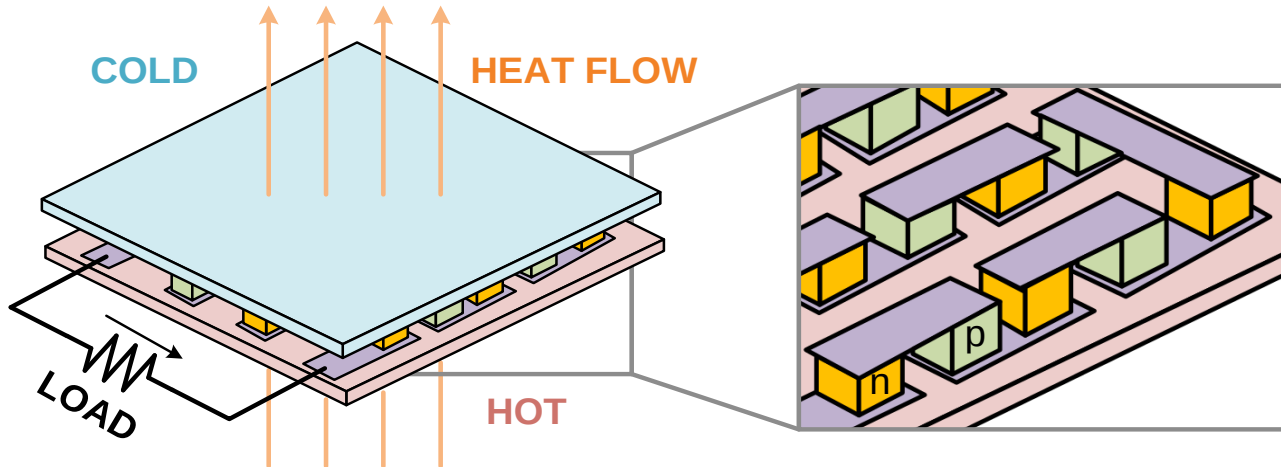
Opportunity: energy harvesting



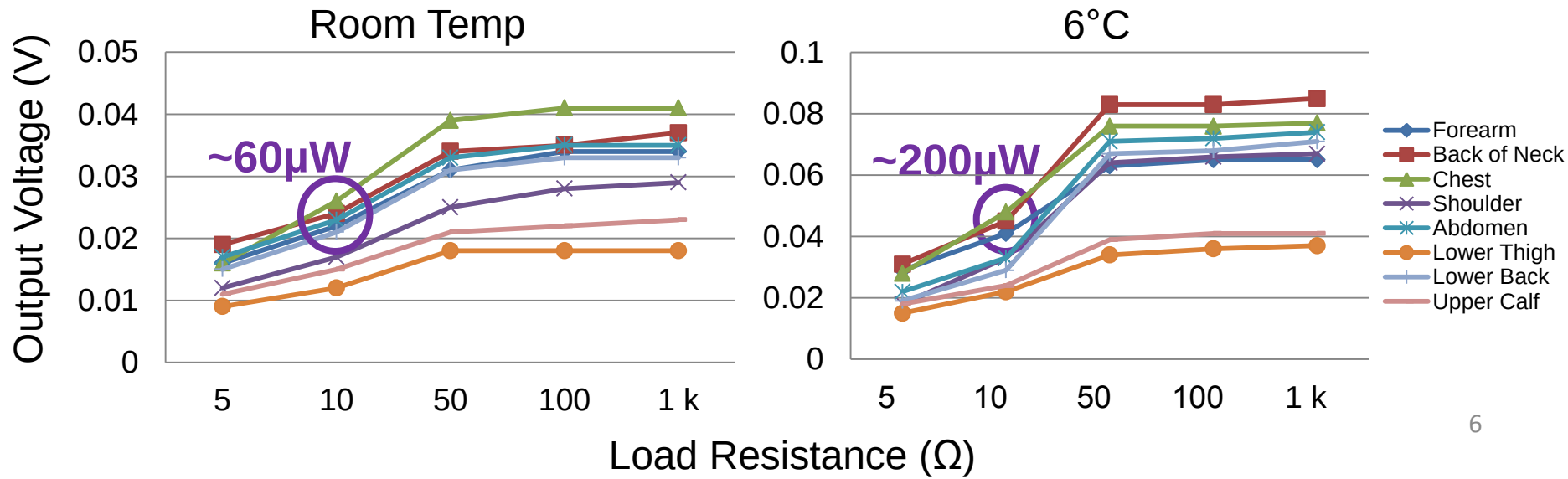
On-body measurement of COTS thermoelectric generator (TEG) (4 x 4 cm²)



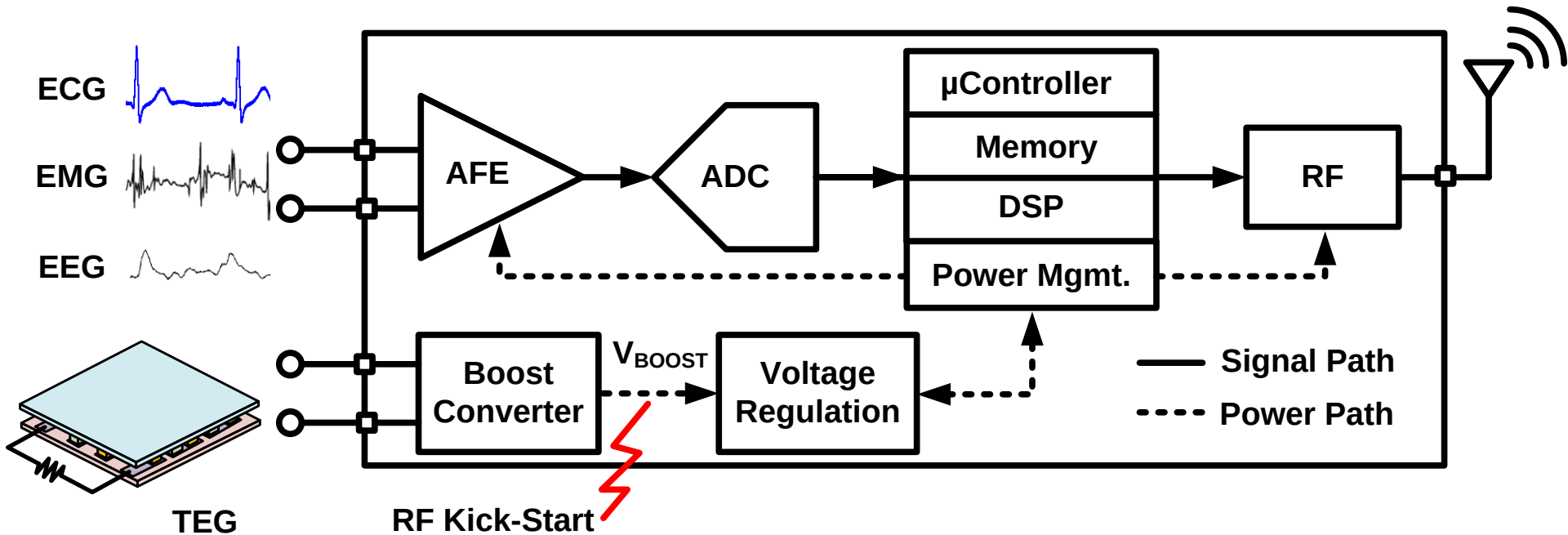
Opportunity: energy harvesting



On-body measurement of COTS thermoelectric generator (TEG) (4 x 4 cm²)



Our proposed solution



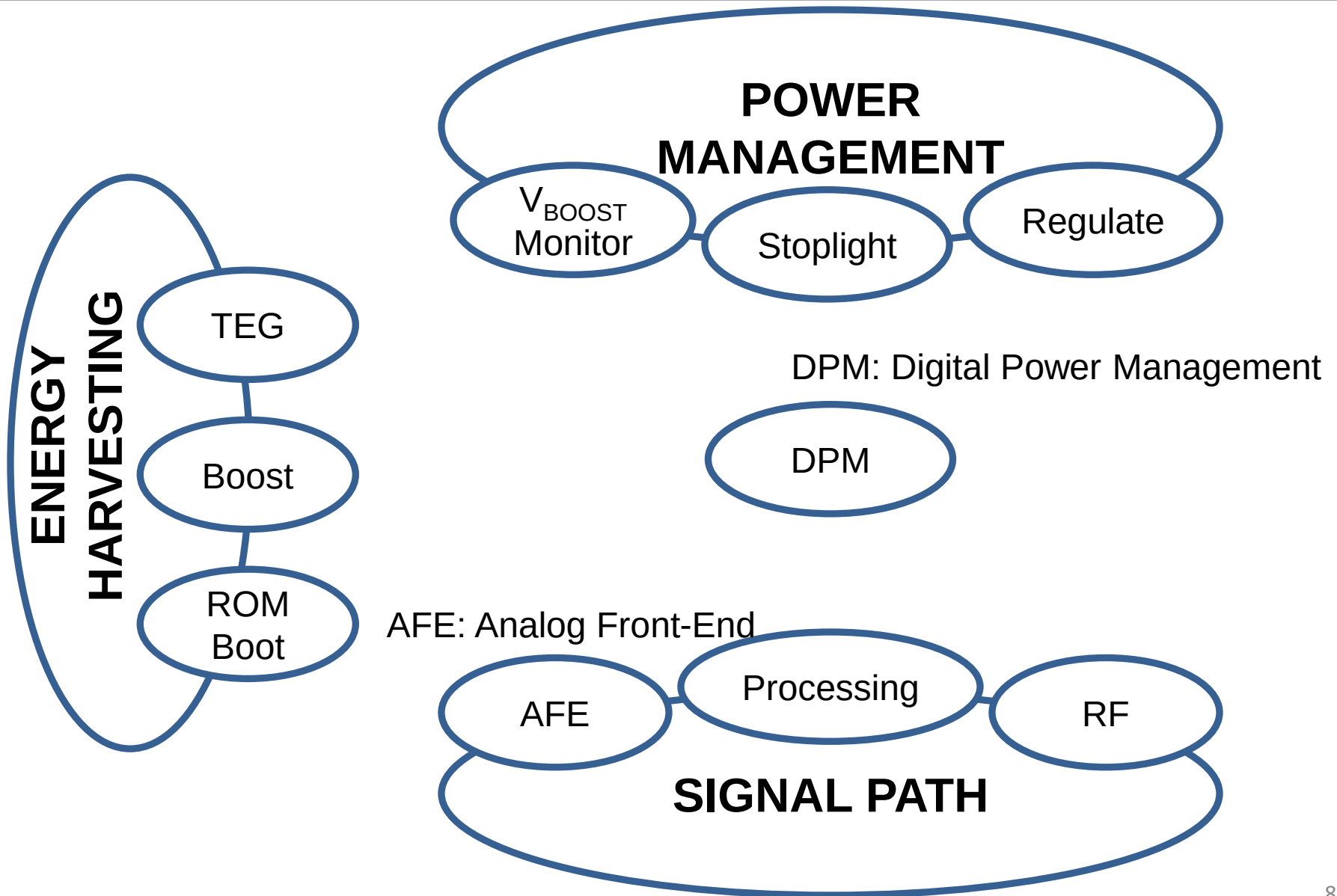
CONVENTIONAL:

- Battery
- No signal processing
- Transmission at 100% DC

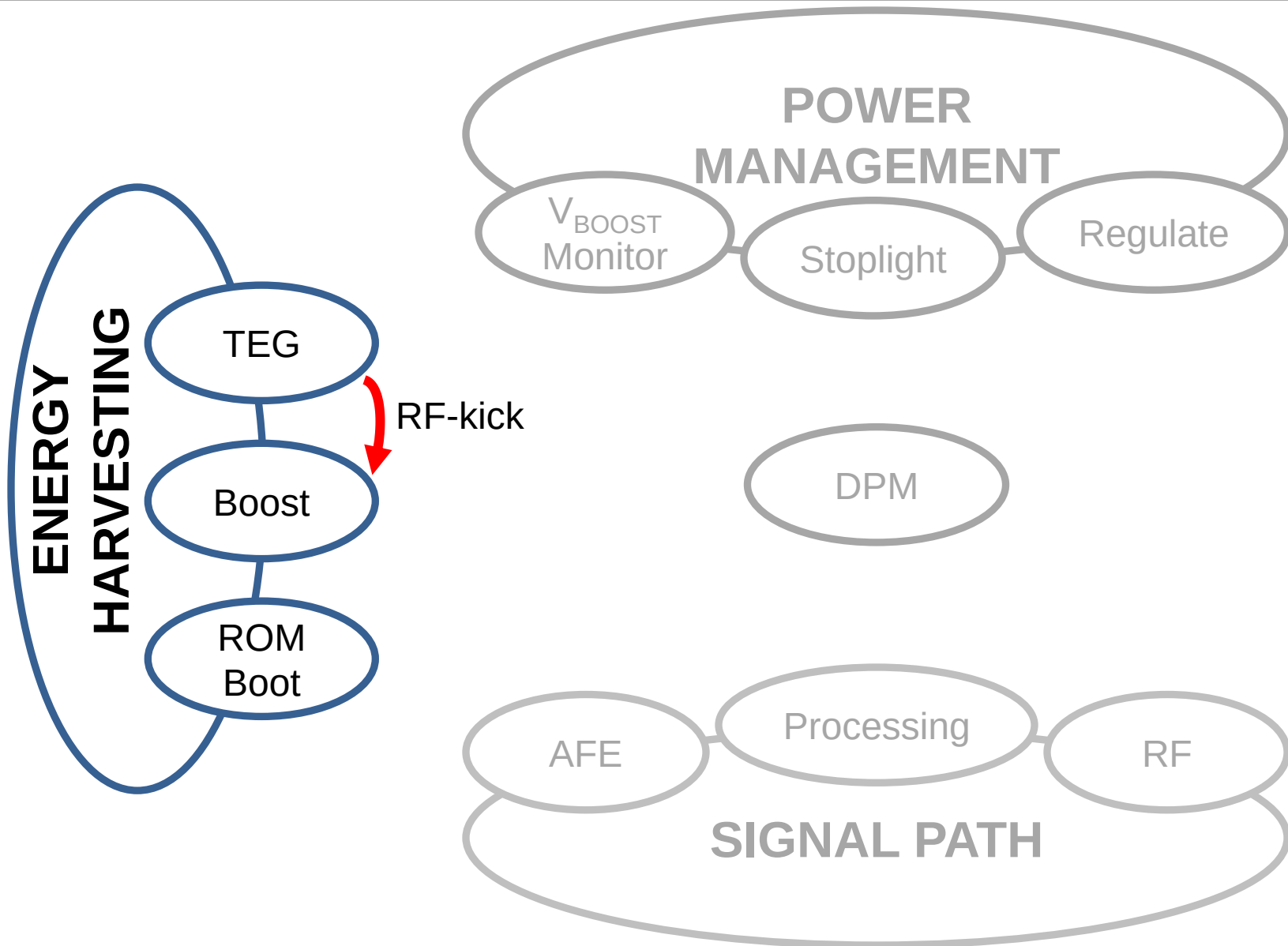
PROPOSED:

- **NO** battery $\rightarrow$ harvest power
- Extract information
- Selective transmission

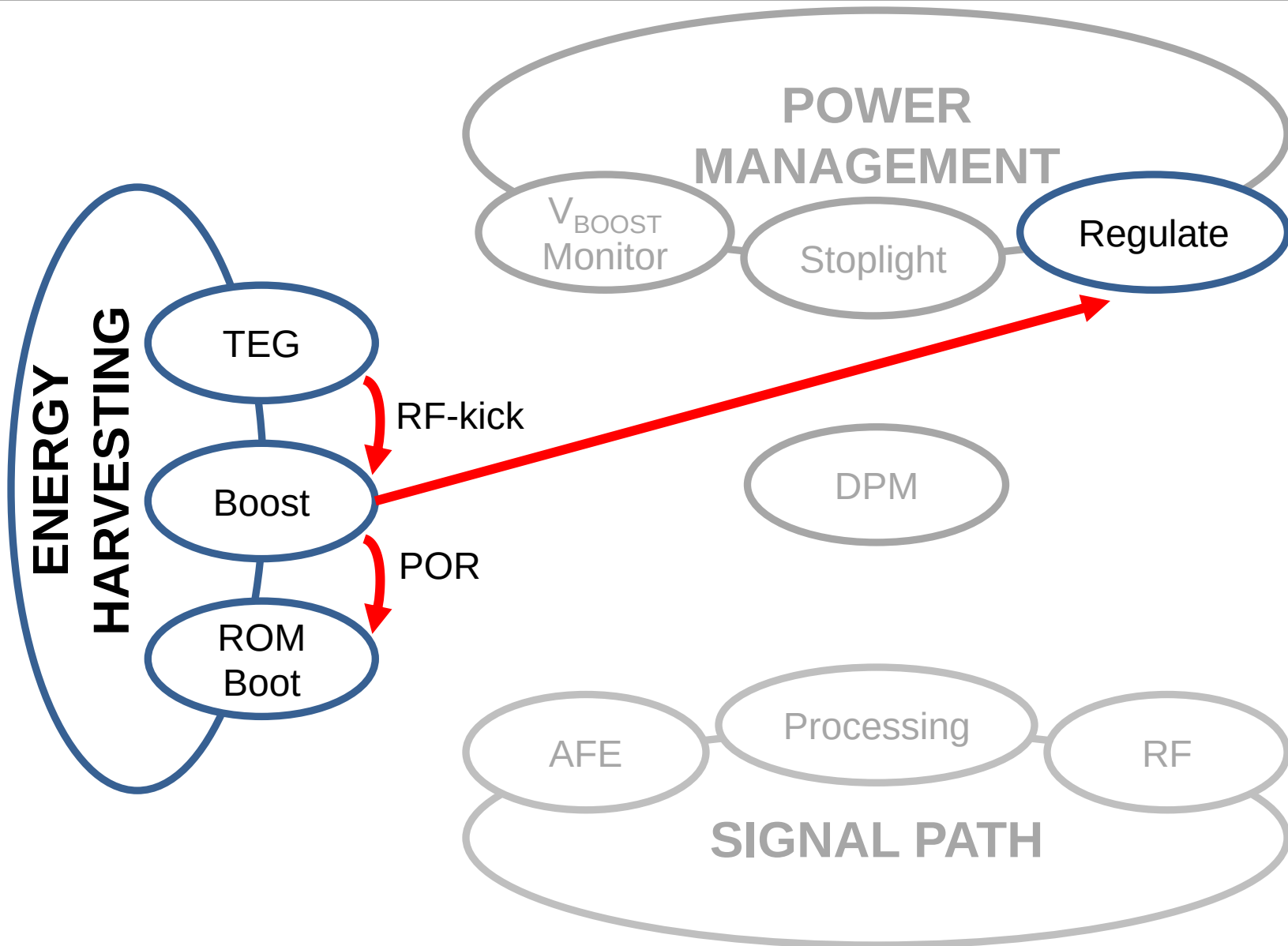
Functional diagram



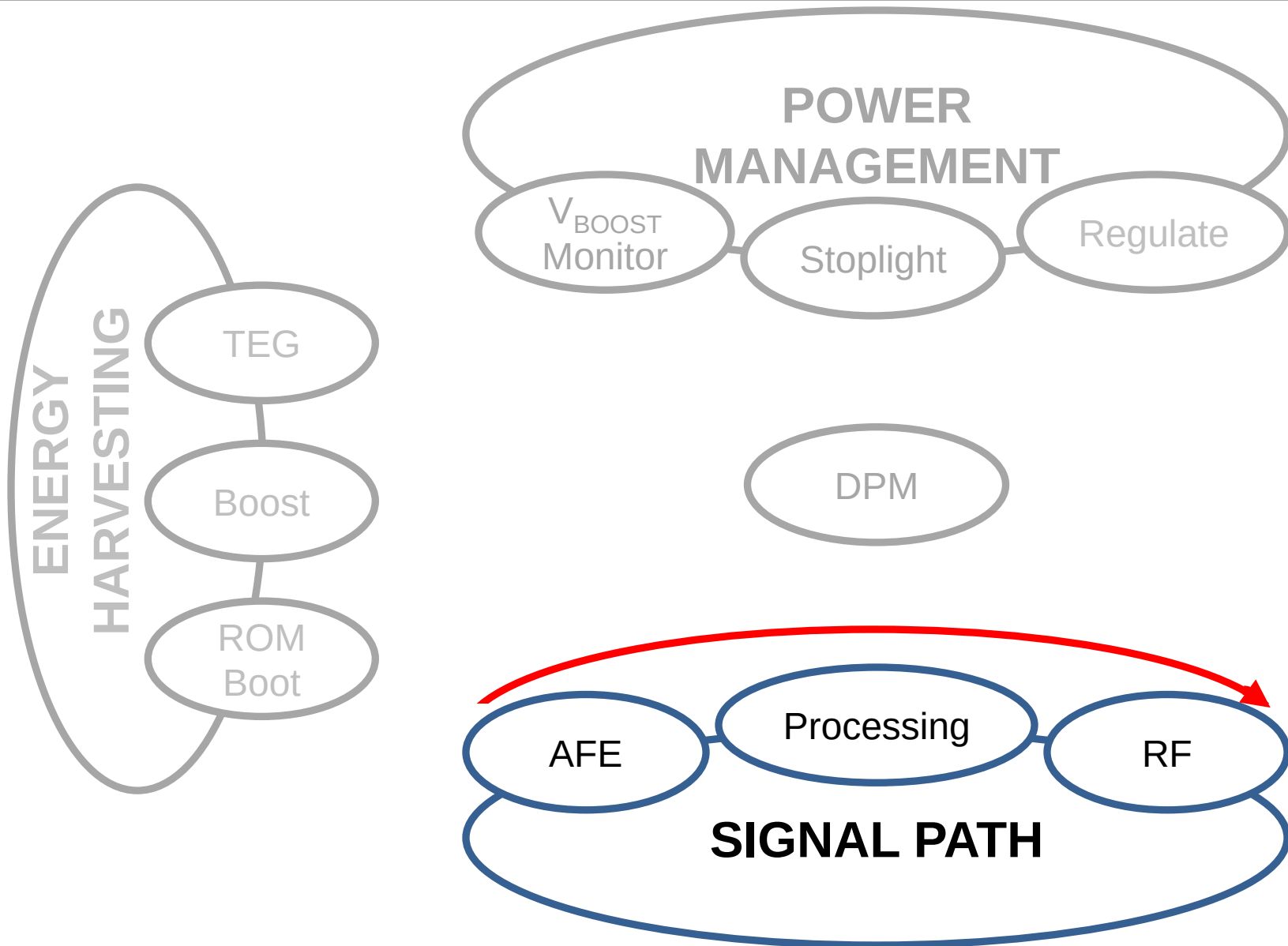
Startup and energy harvesting



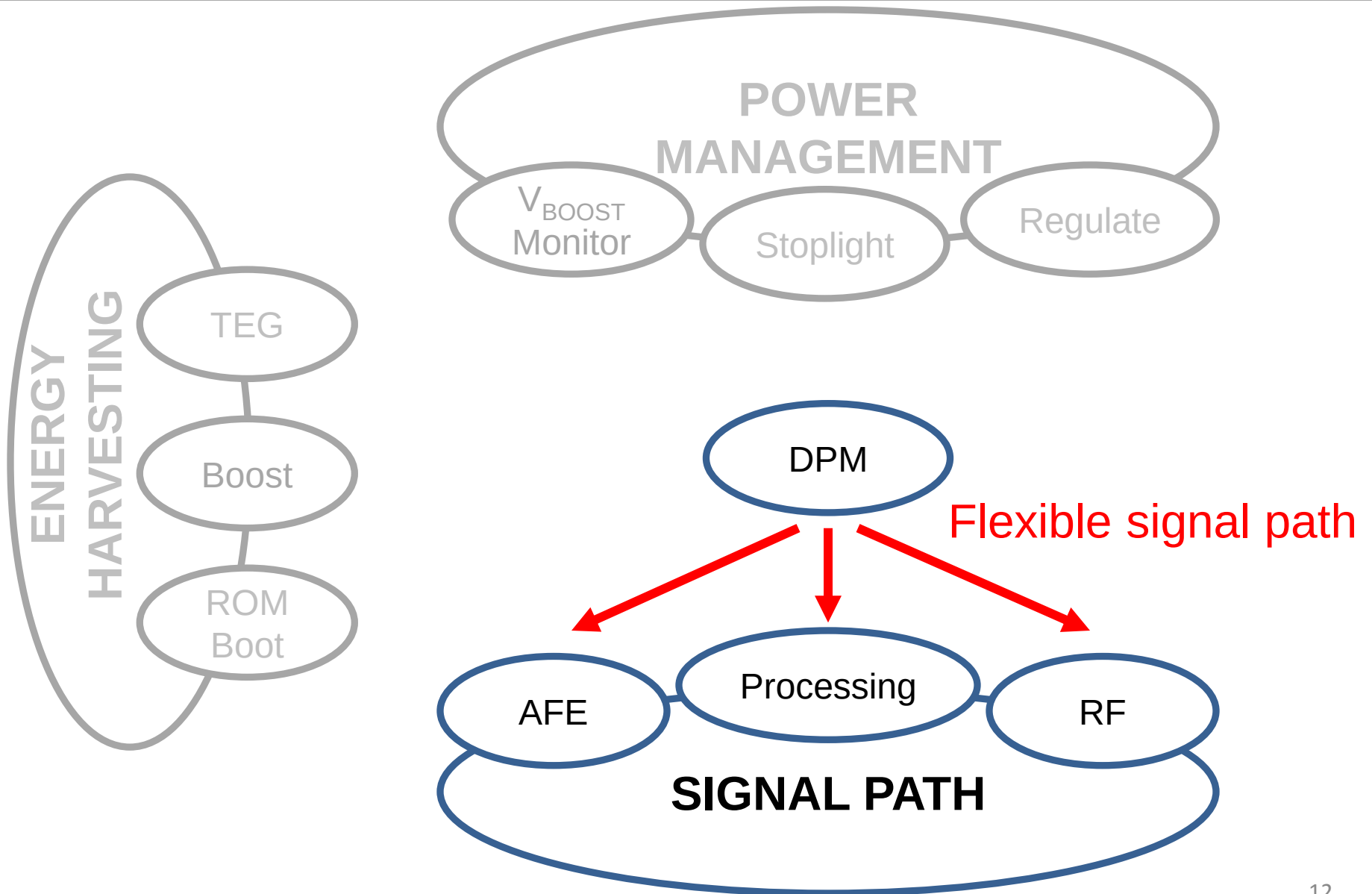
Startup and energy harvesting



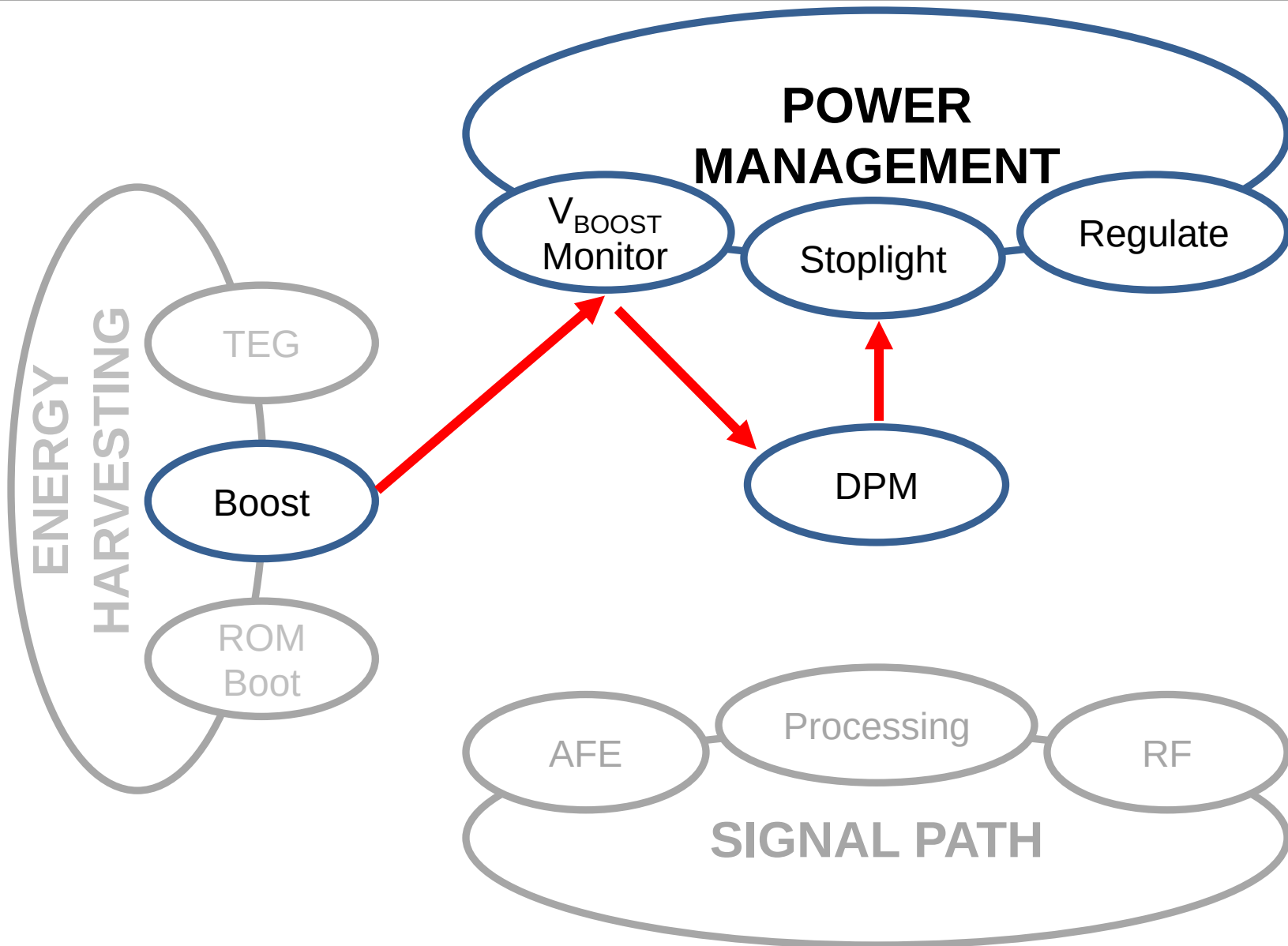
Signal processing path



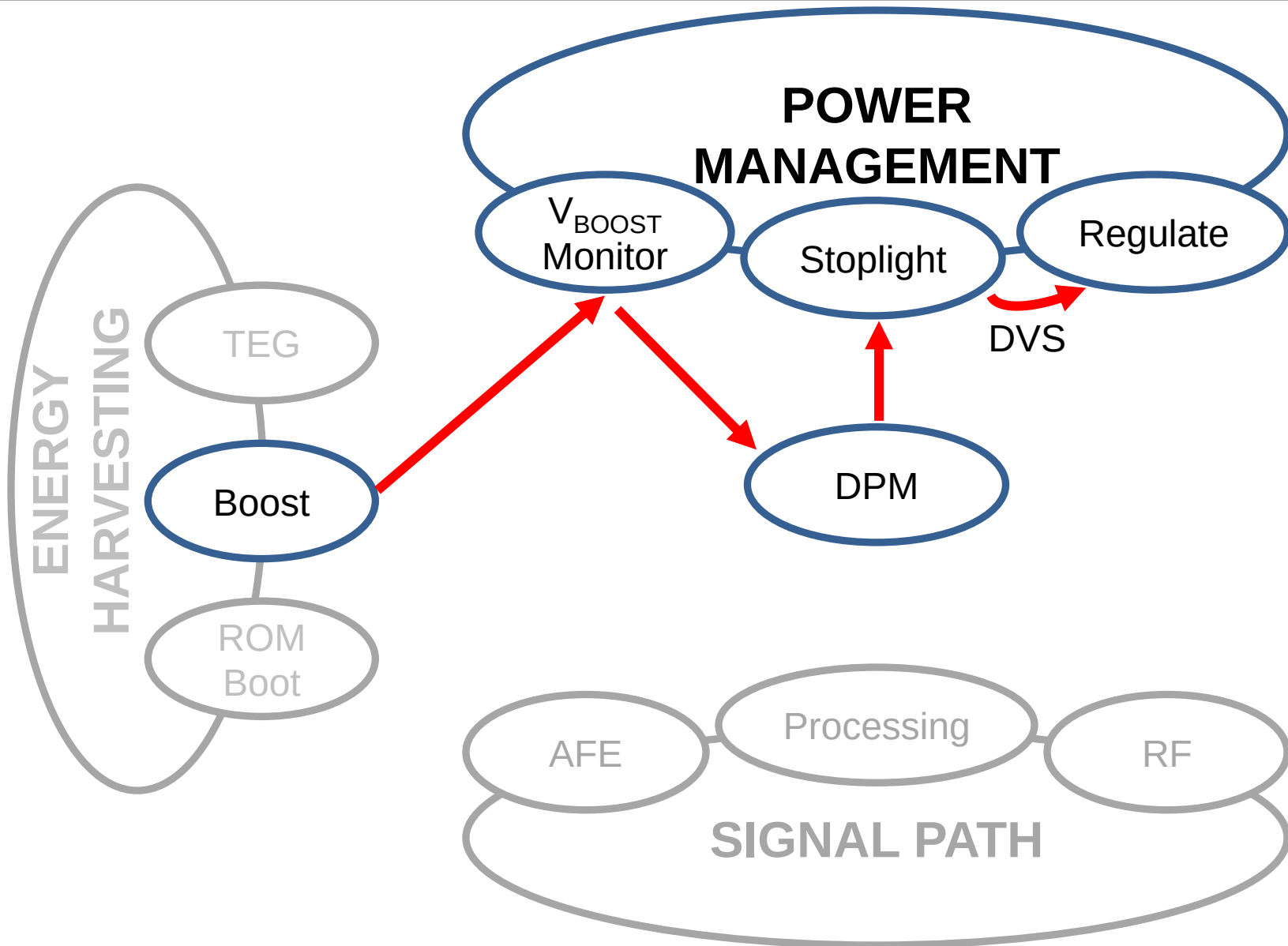
Signal processing path



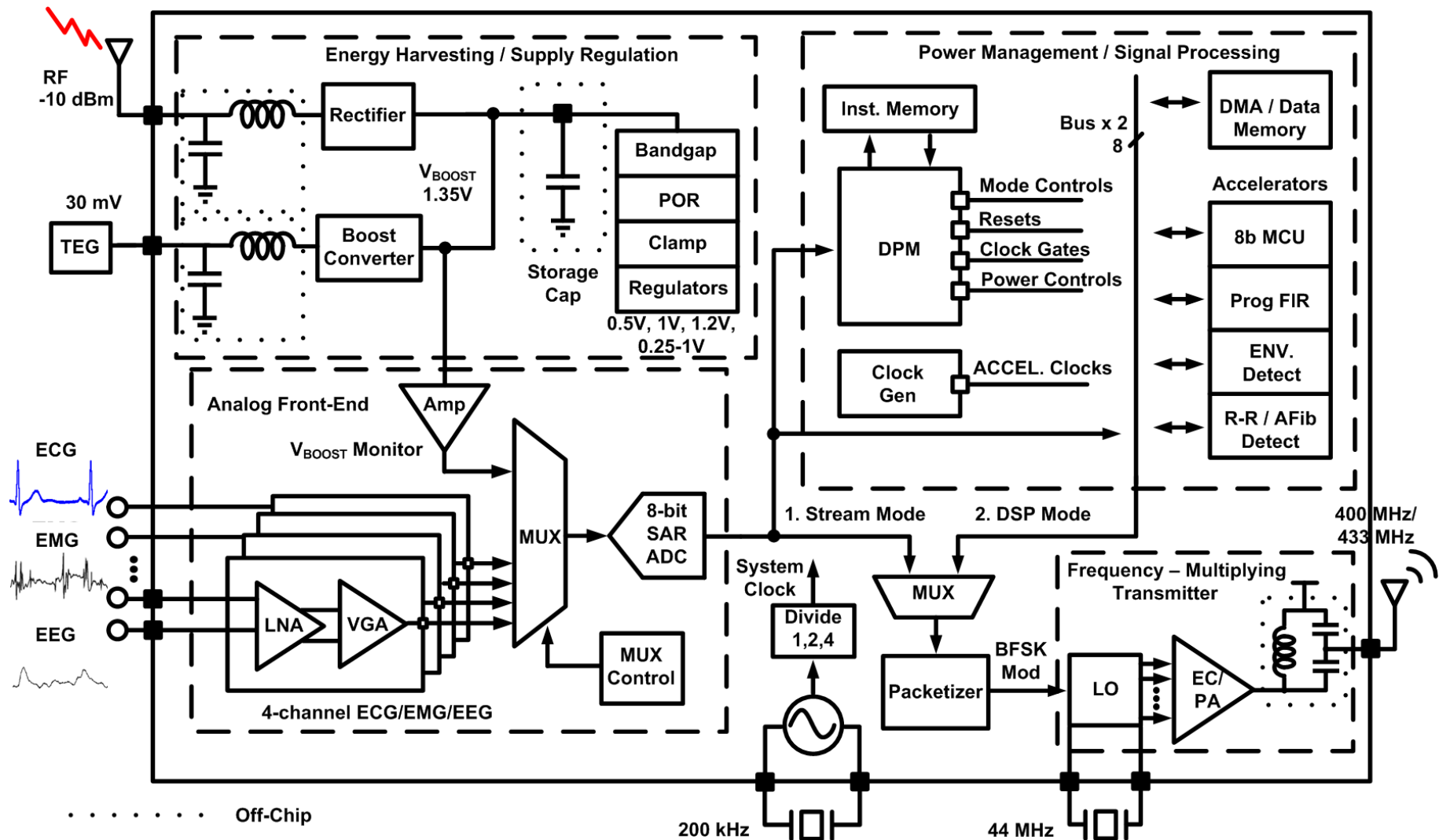
Power management



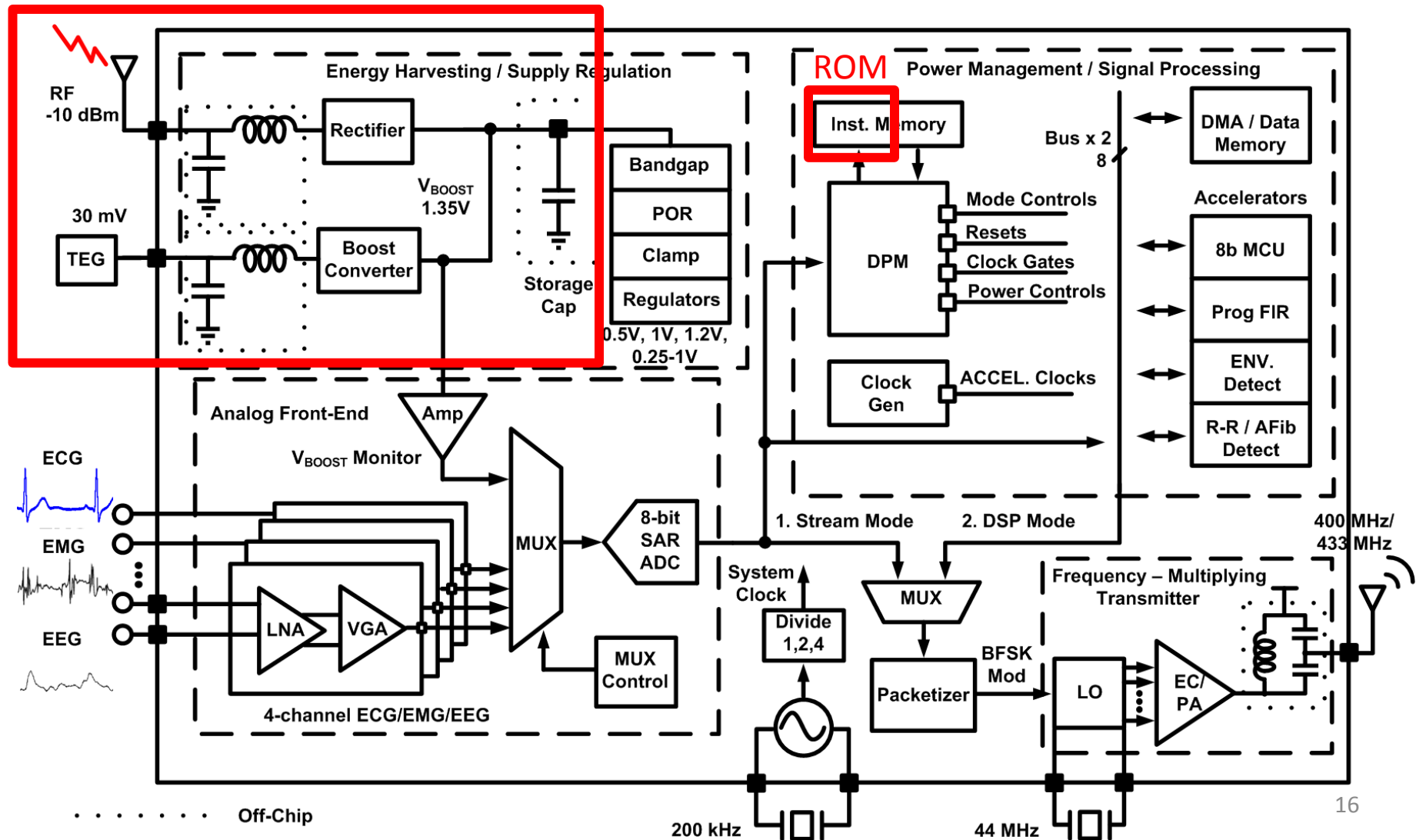
Power management



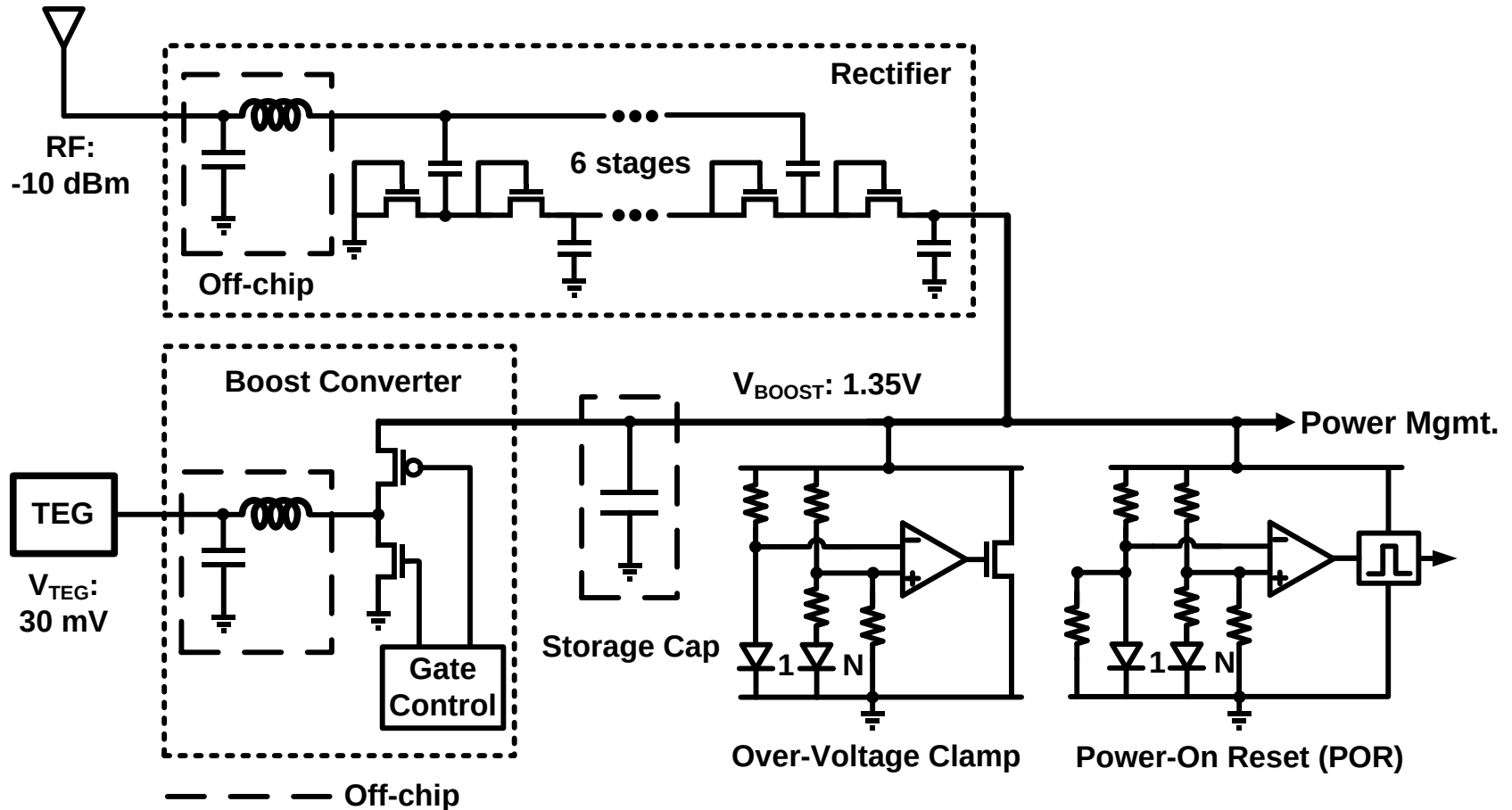
System block diagram



Energy harvesting

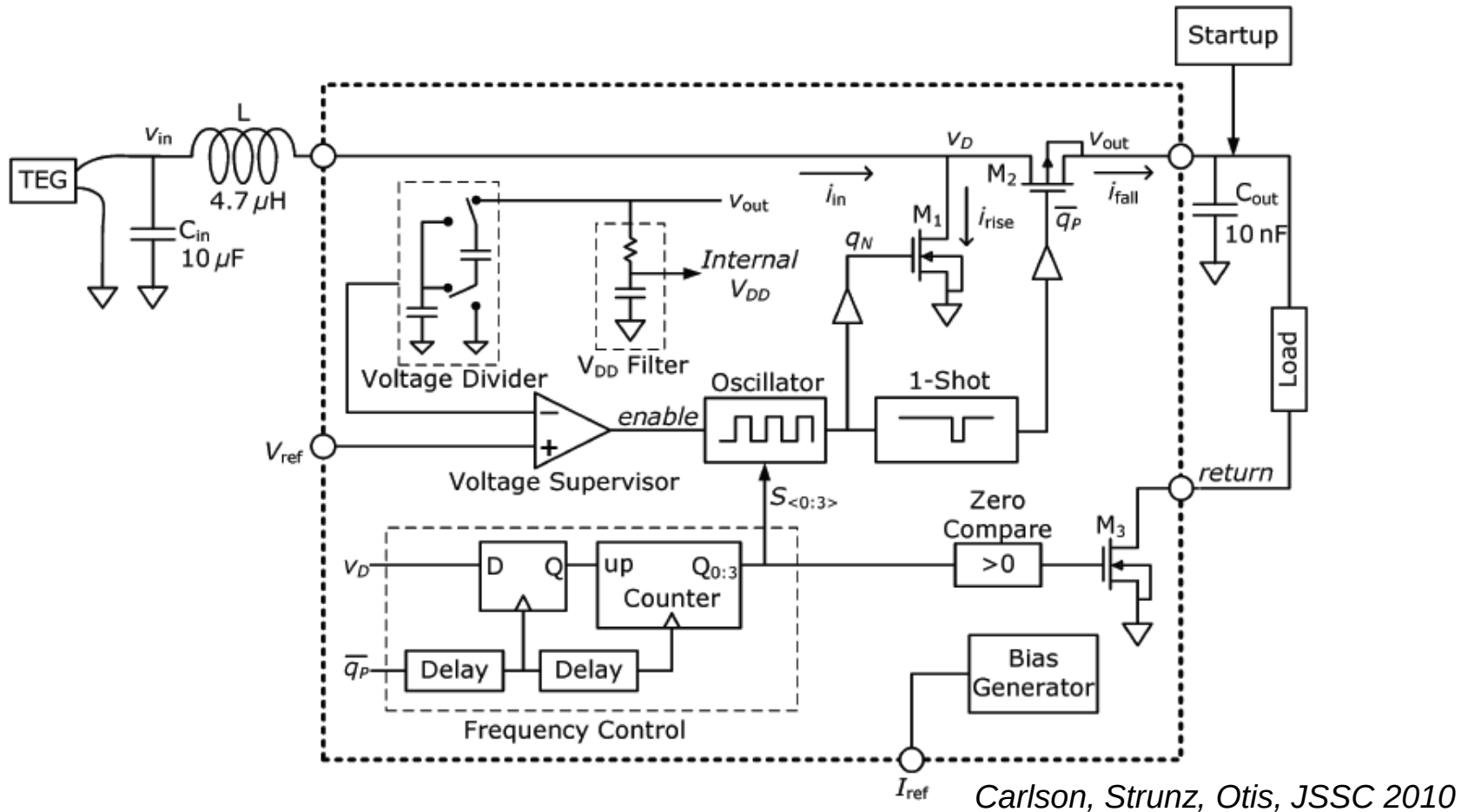


Hybrid energy harvesting



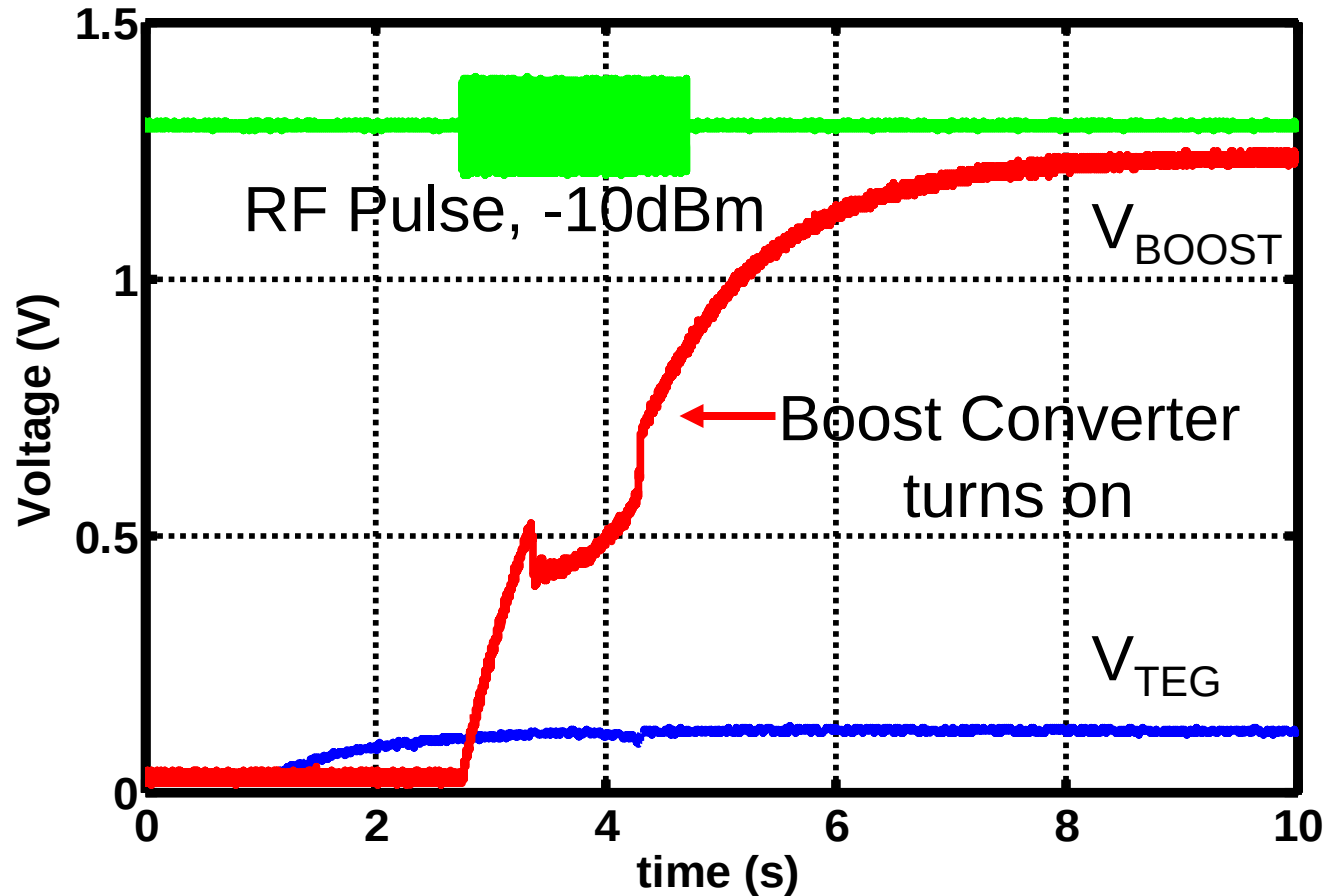
Capable of thermal, photovoltaic, and/or RF energy harvesting

Boost converter



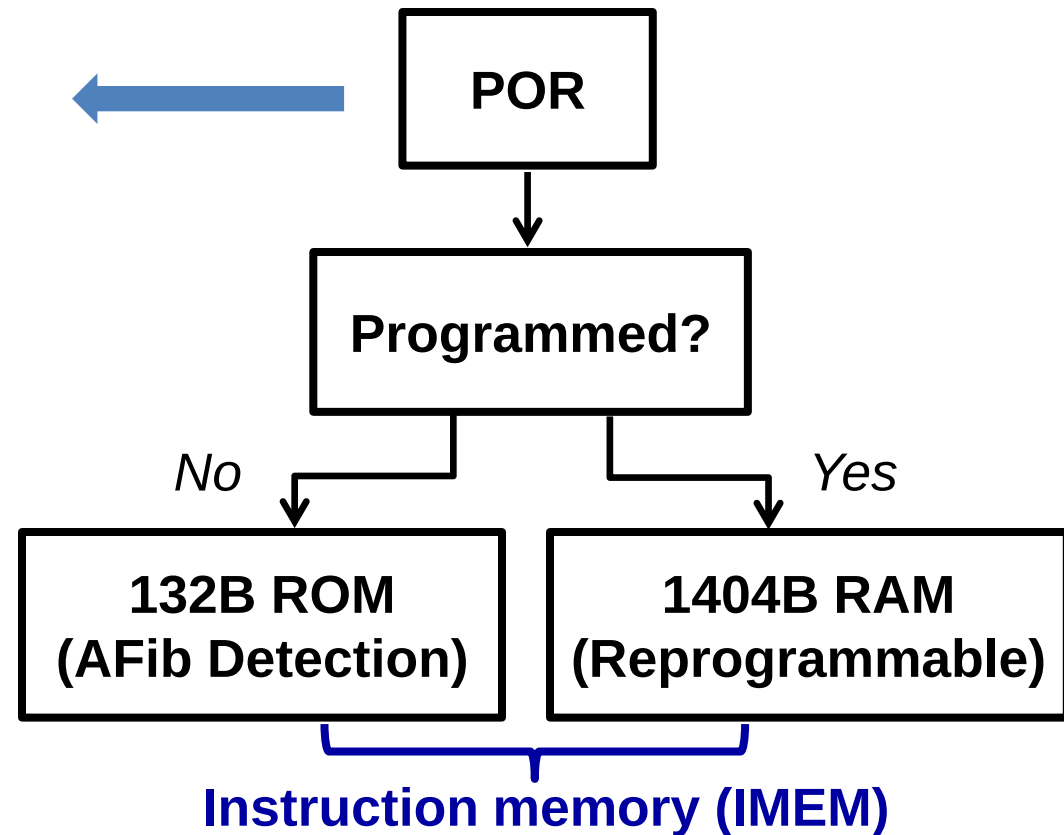
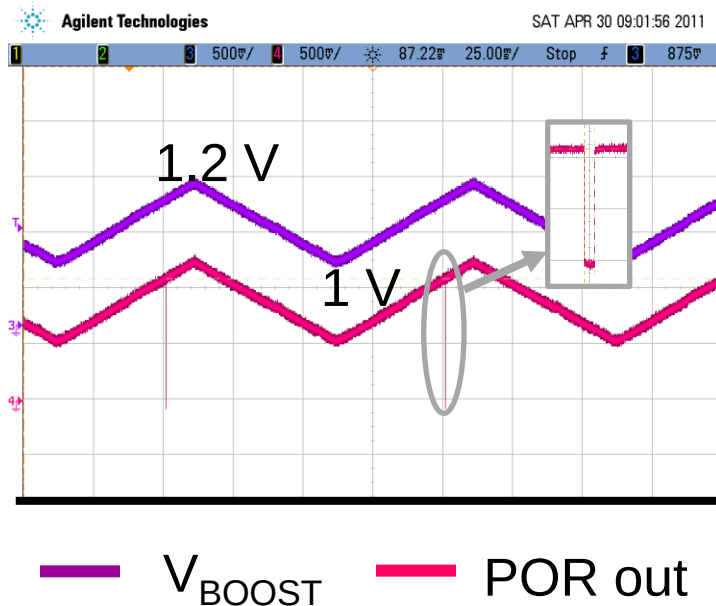
- Measured efficiency of 38% for $V_{in}=30\text{mV}$, $V_{out}=1.35\text{V}$
- Requires minimum voltage (V_{KILL}) to sustain conversion

Measured RF kick-start



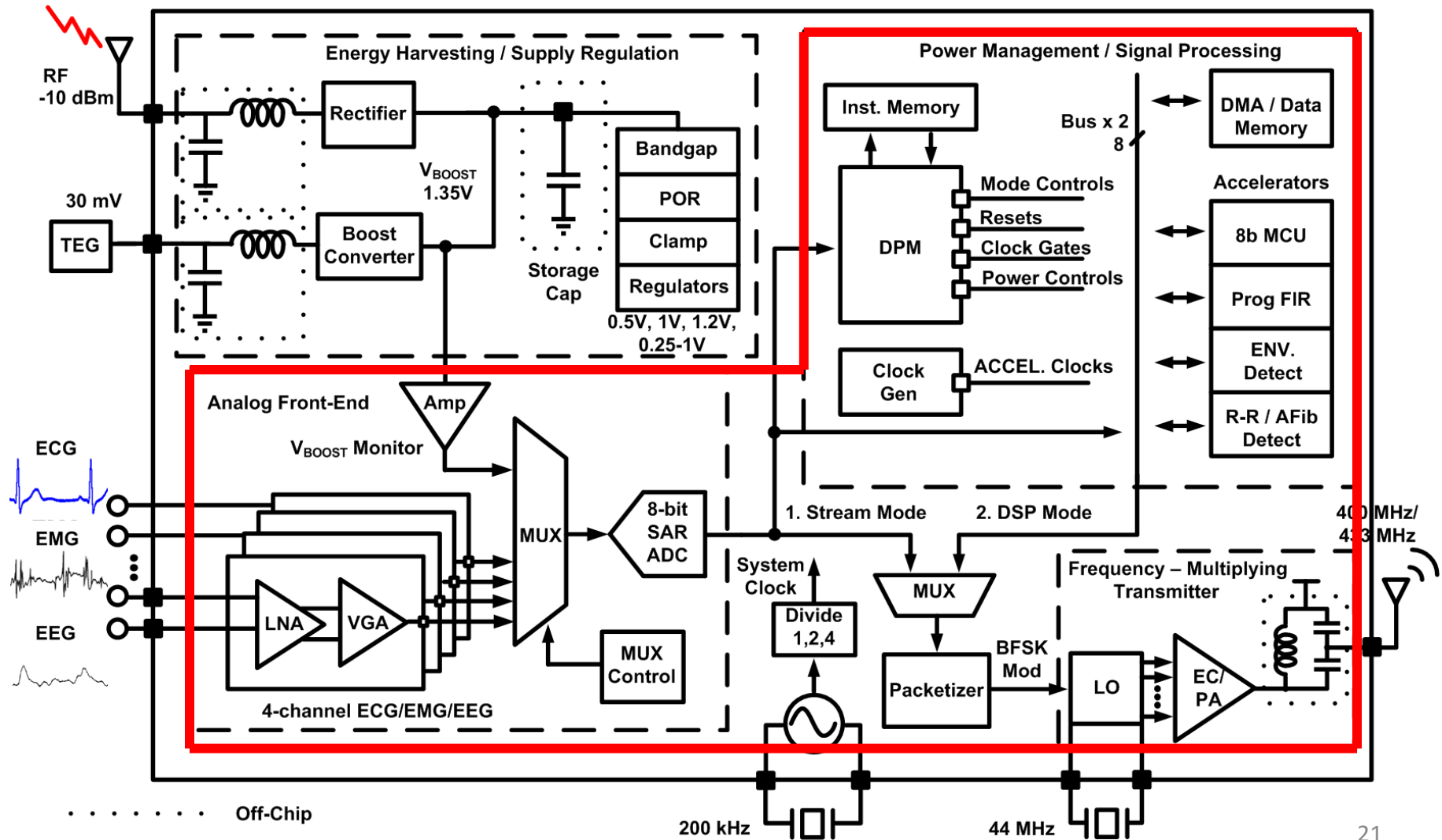
- Wireless RF pulse provides one-time kick-start
- The node runs indefinitely thereafter

Boot-up sequence



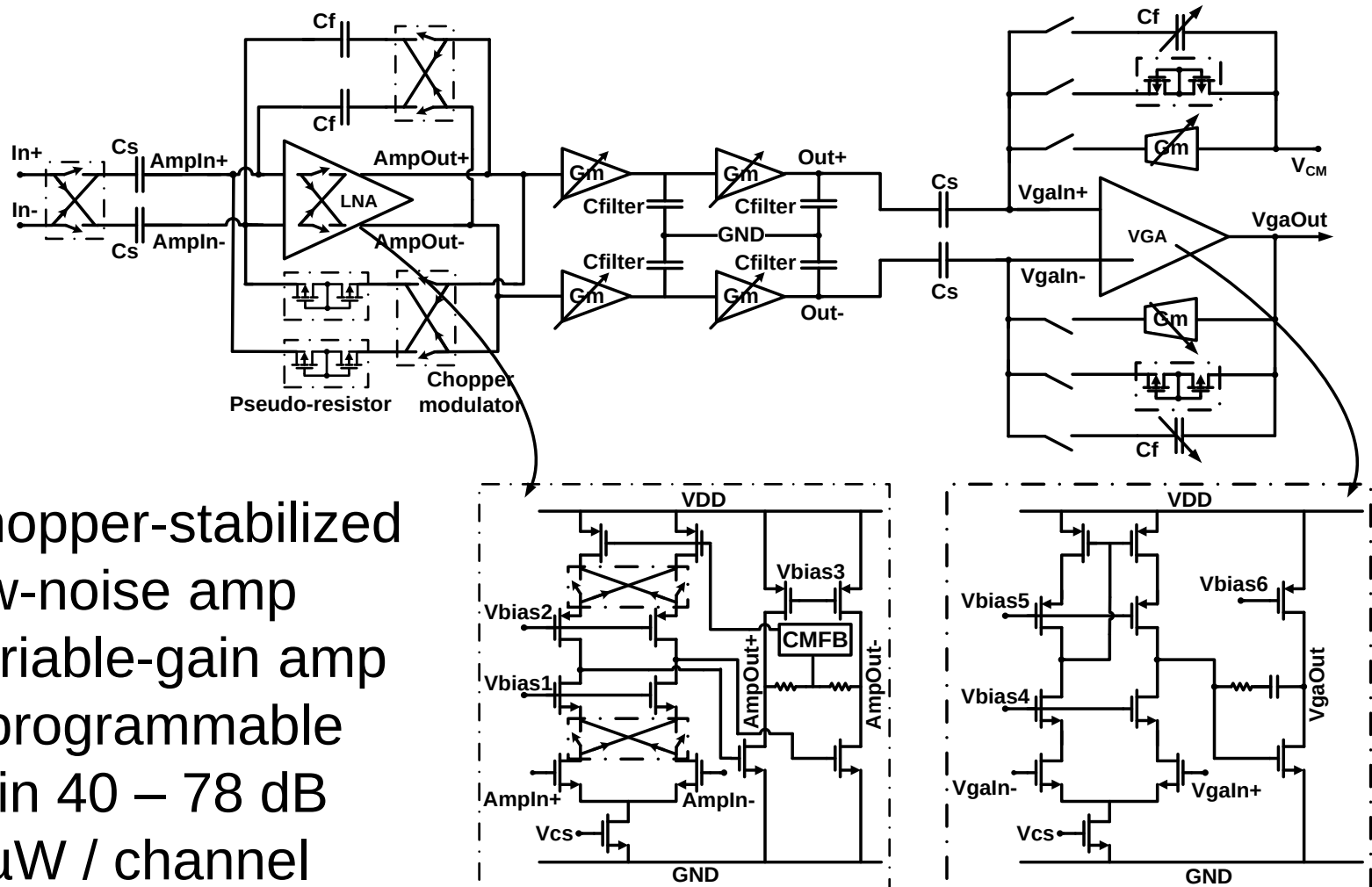
- POR issues reset at 1.0V
- Upon boot-up, the chip fetches instructions from the ROM (default) or the RAM
- If $V_{\text{BOOST}} < V_{\text{KILL}}$, RF burst can 'revive' chip to default algorithm in ROM

Signal path



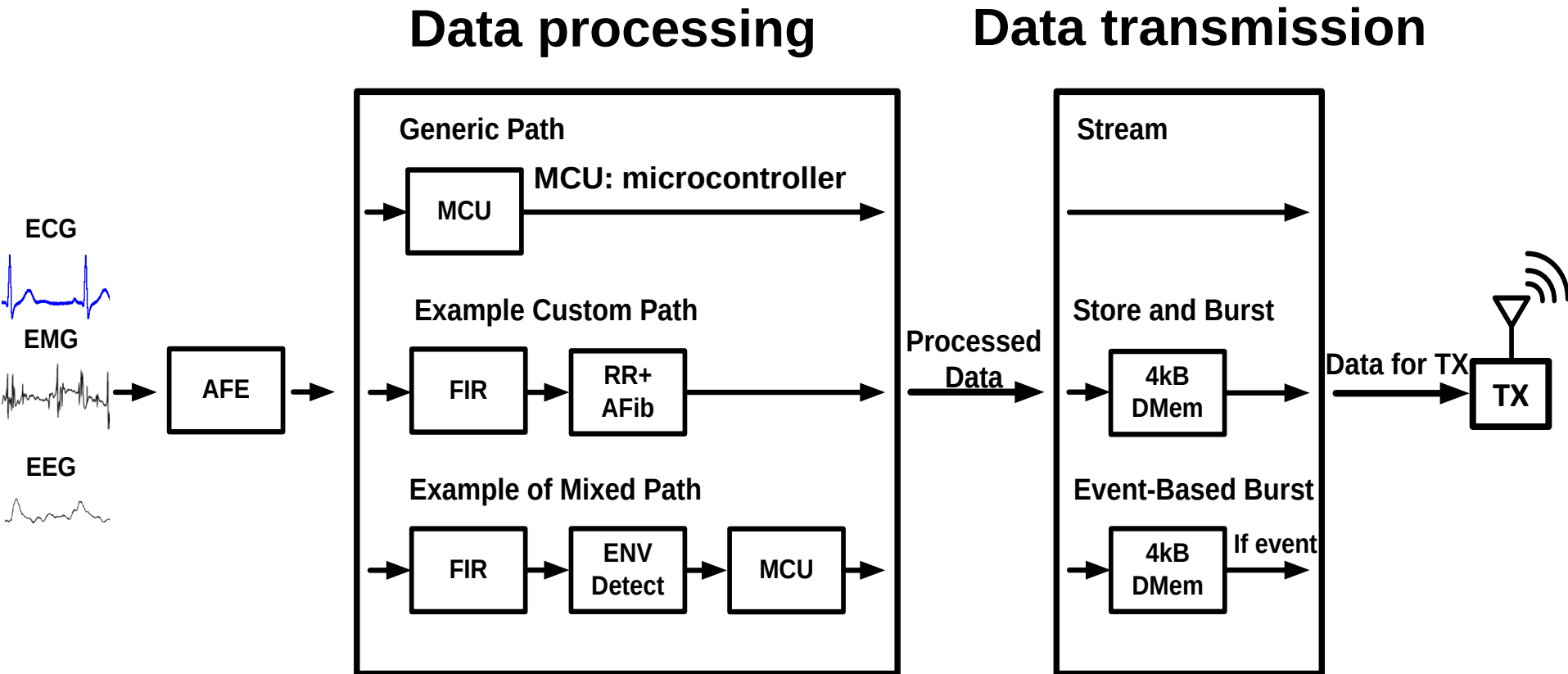
Analog front-end (AFE)

1 of 4 channels



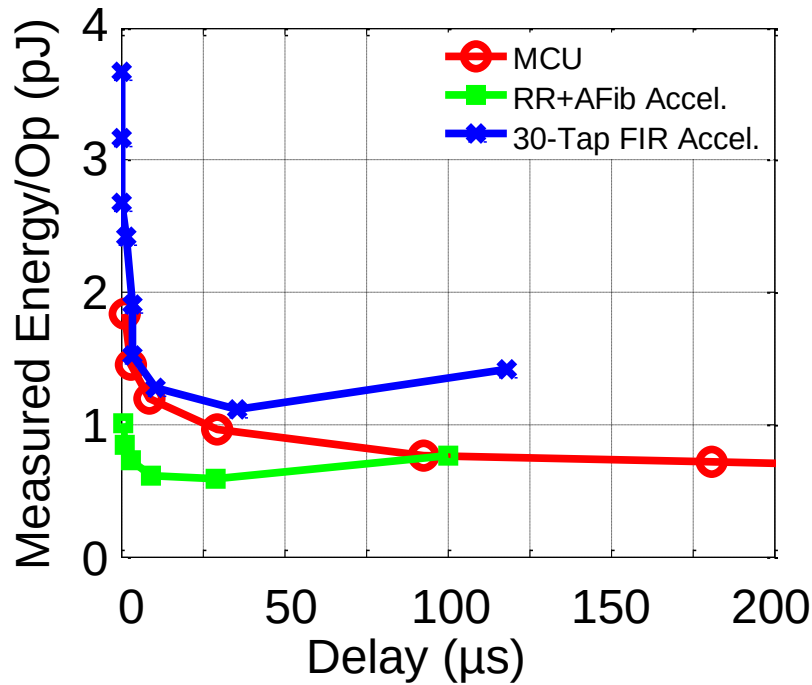
- Chopper-stabilized low-noise amp
- Variable-gain amp
- 6 programmable gain 40 – 78 dB
- 3 μW / channel

Flexible signal path



- Data processing: max flexibility (generic path) or max efficiency (biosignal accelerators)
- Data transmission: supports modes from streaming (100% DC) to rare event detection (~0% DC)

Energy efficient accelerators



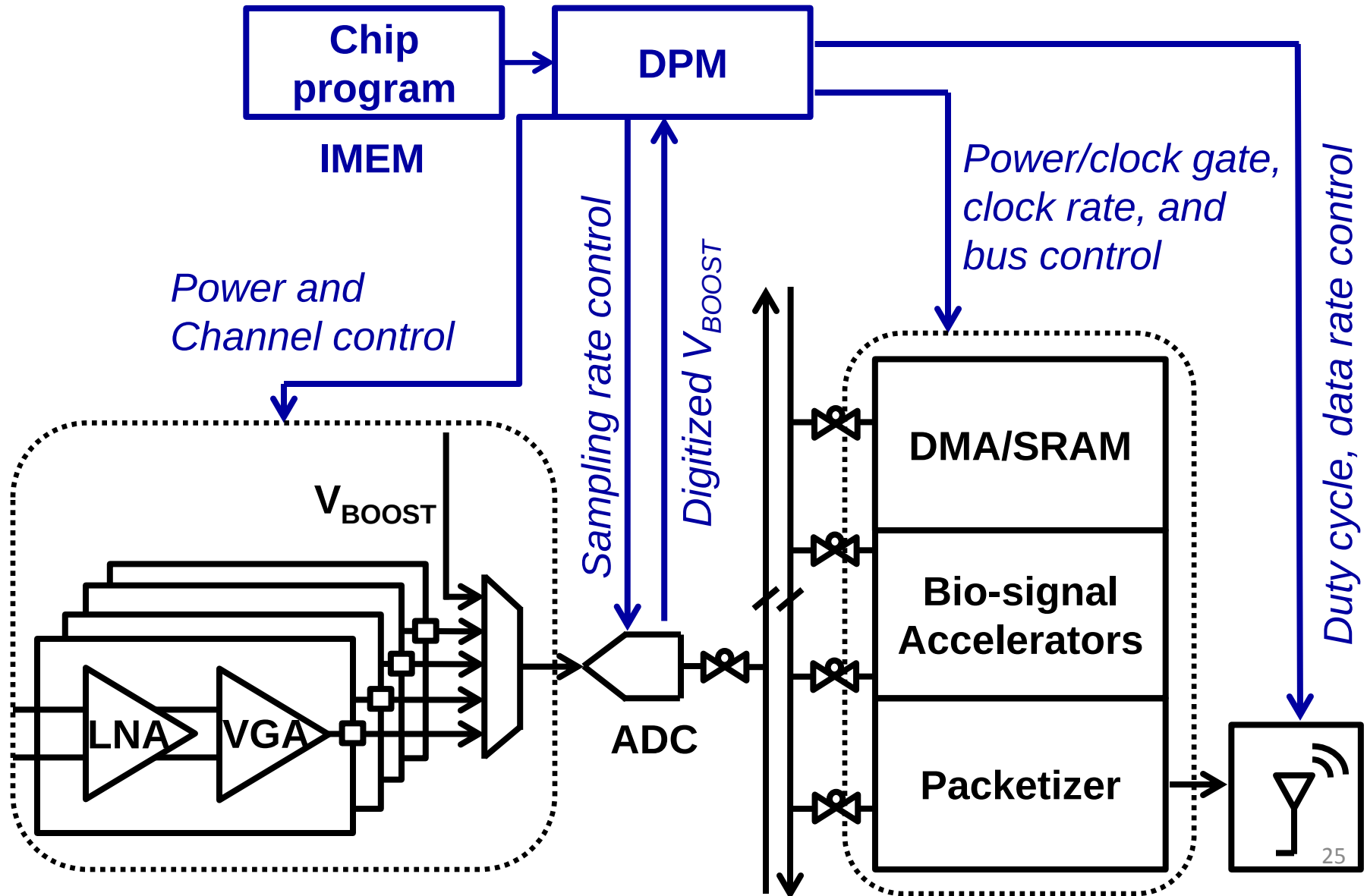
Accelerators:

- Programmable FIR
- Heart rate (R-R) extraction
- Atrial Fibrillation (AFib) detection
- Band energy extraction
- Direct memory access (DMA)
- Packetizer

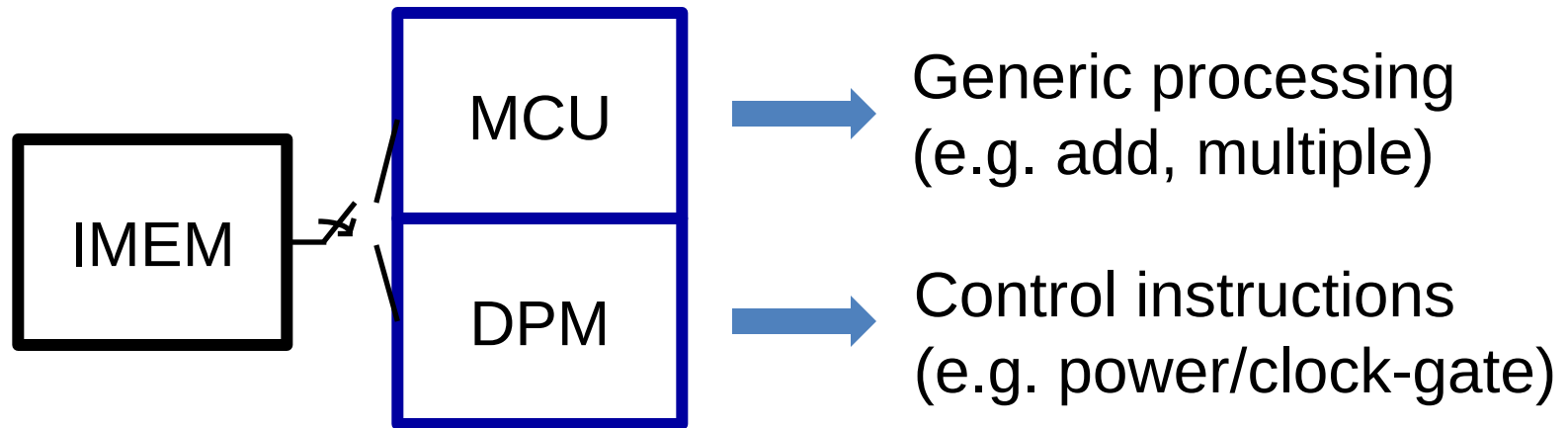
Energy Efficiency / Sample

30 Tap FIR	MCU	6.3 nJ	↘ 110x
	Accel	57.6 pJ	
Env. Detect	MCU	3.6 nJ	↘ 6800x
	Accel	530 fJ	
R-R Extract	MCU	12 pJ	↘ 4000x
	Accel	3 fJ	

DPM: signal path control



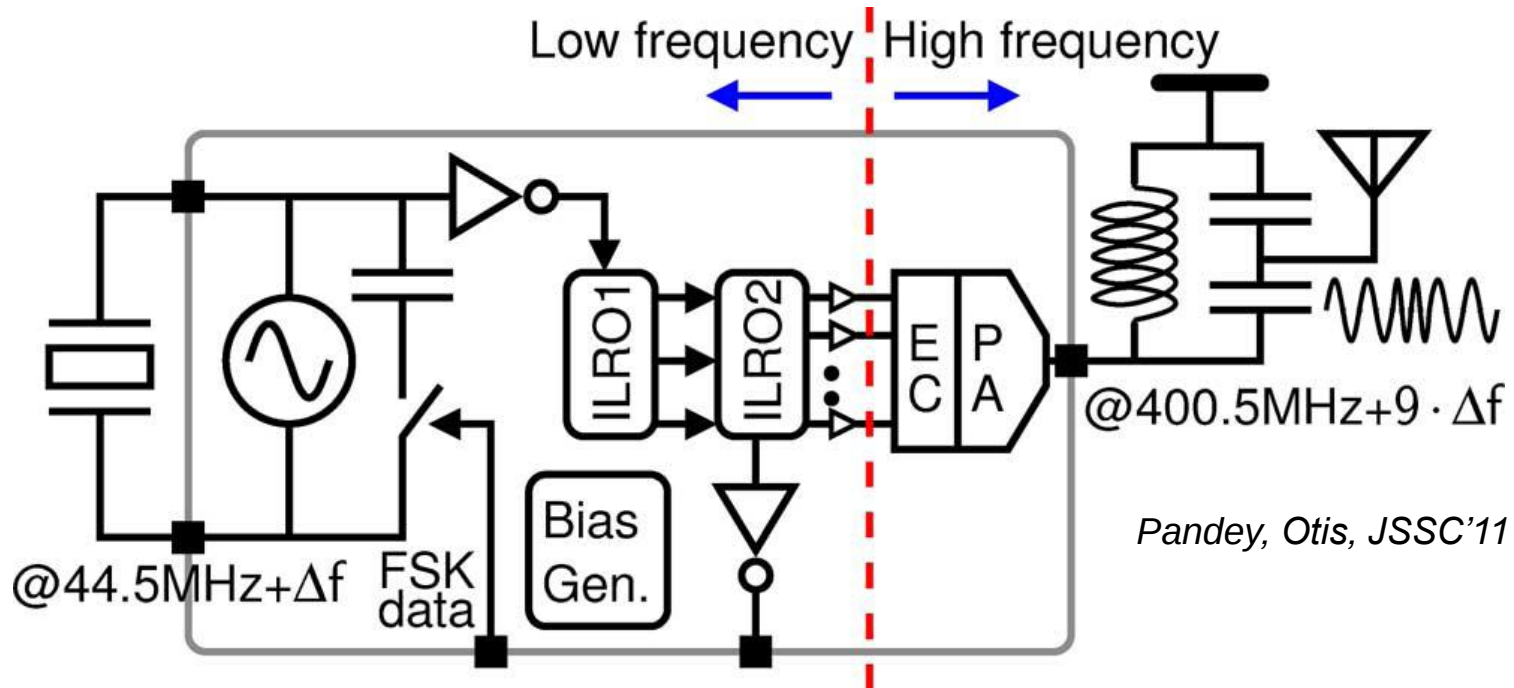
MCU vs. DPM



- Execution of instructions toggles automatically between MCU and DPM.

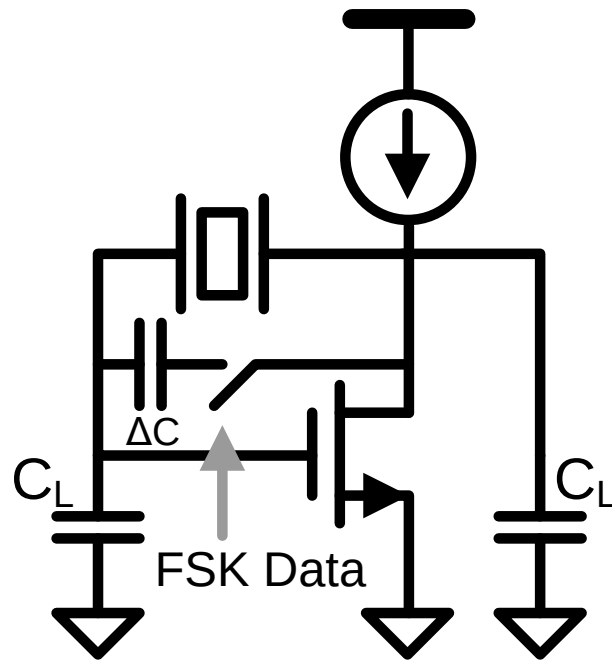
Operation	DPM Energy	MCU Energy
NOP	0.7 pJ	1.46 pJ
Control Signals	2.8 pJ	2.92 pJ
Branch Commands	2.9 pJ	4.38 pJ

Frequency multiplying TX

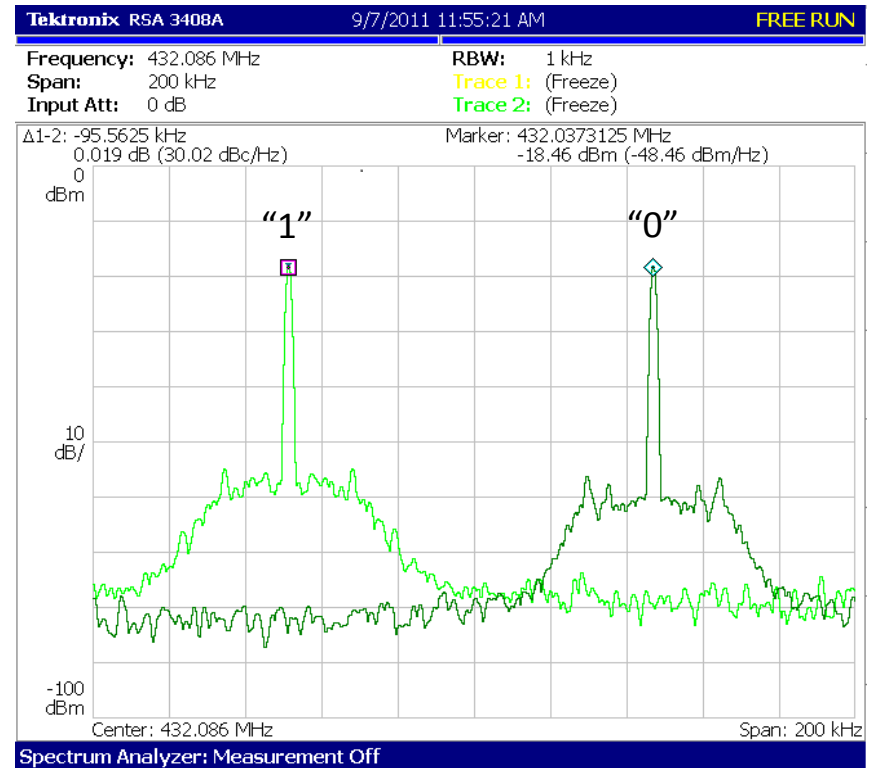


- Frequency multiplication:
synthesis at **low** frequency, transmission at **high** frequency
- Edge-combiner based frequency multiplier
 - ILRO-based edge generator
 - PA integrates the edge combiner

BFSK data modulation

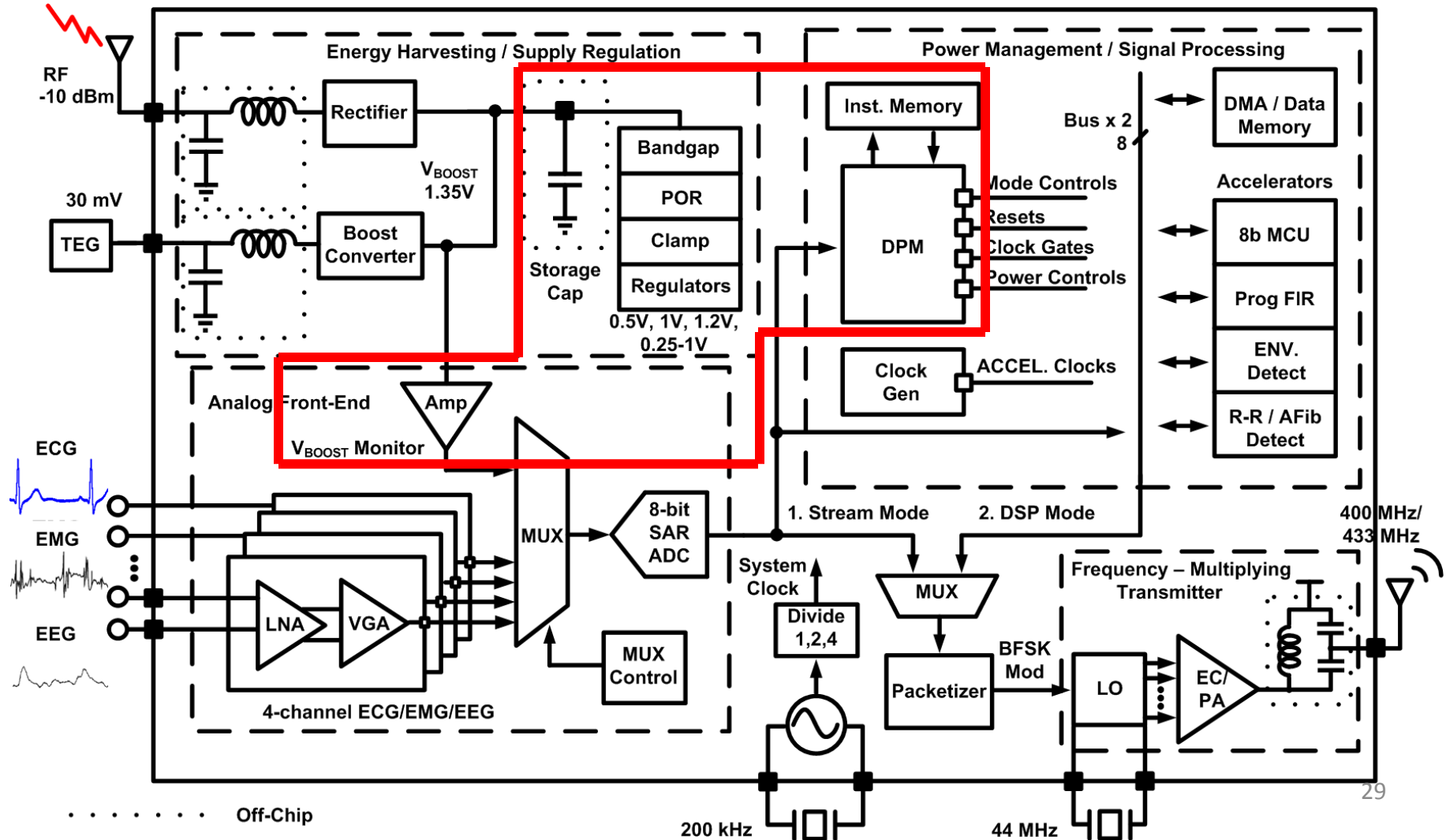


Measured Data Modulation

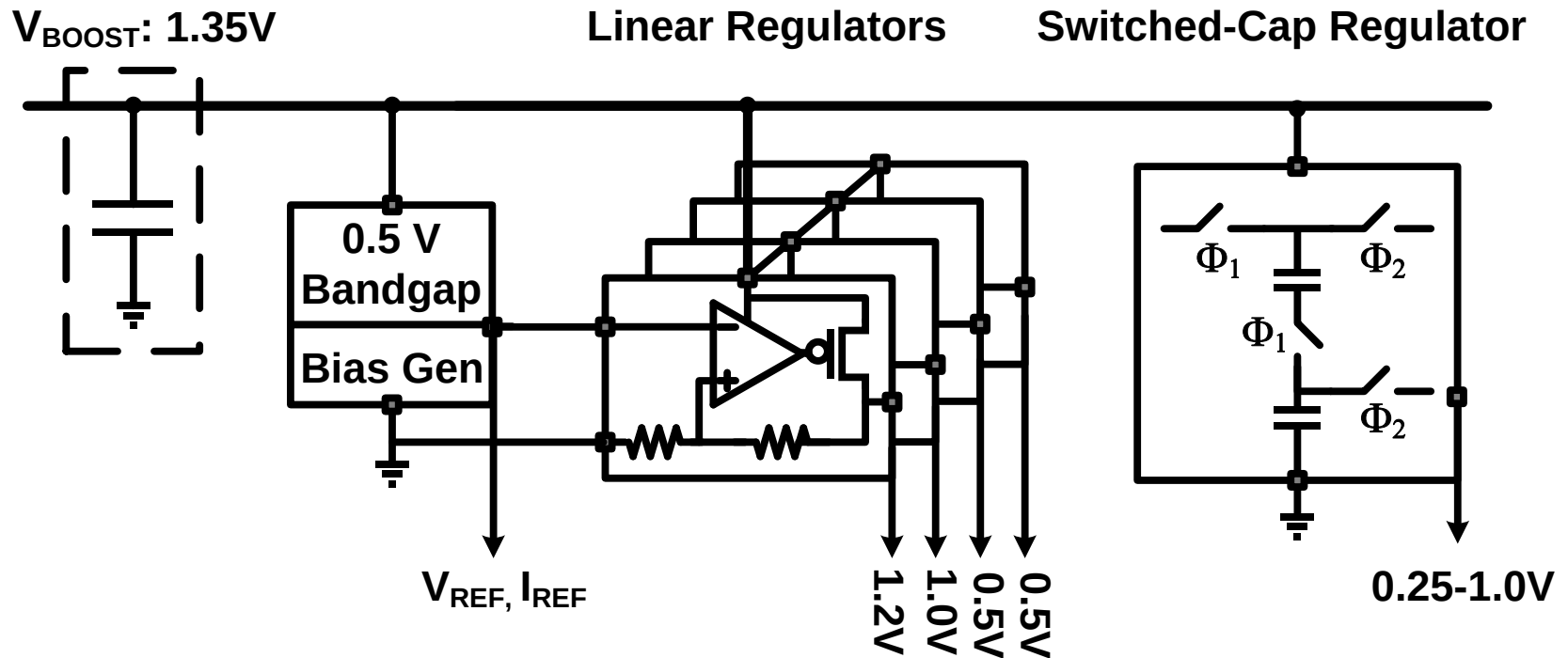


- Quartz reference clock is pulled using ΔC (~ 200 ppm)
- Δf is multiplied by 9x (~ 100 kHz)

Power management

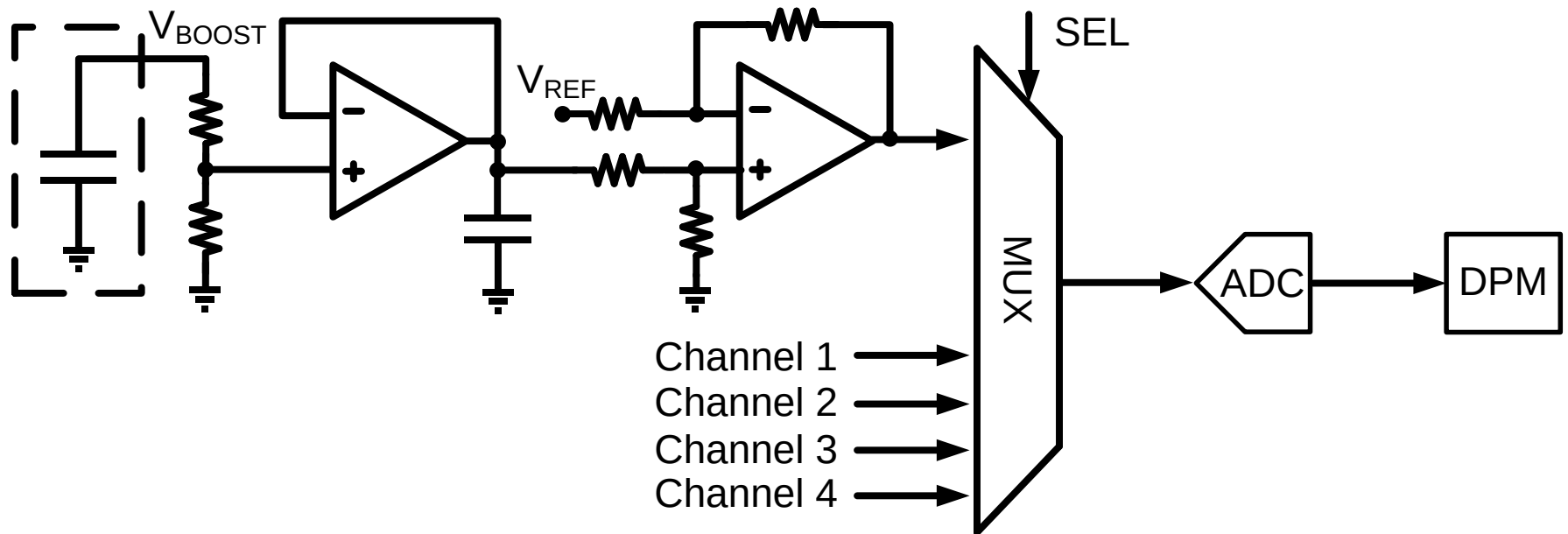


Voltage regulation



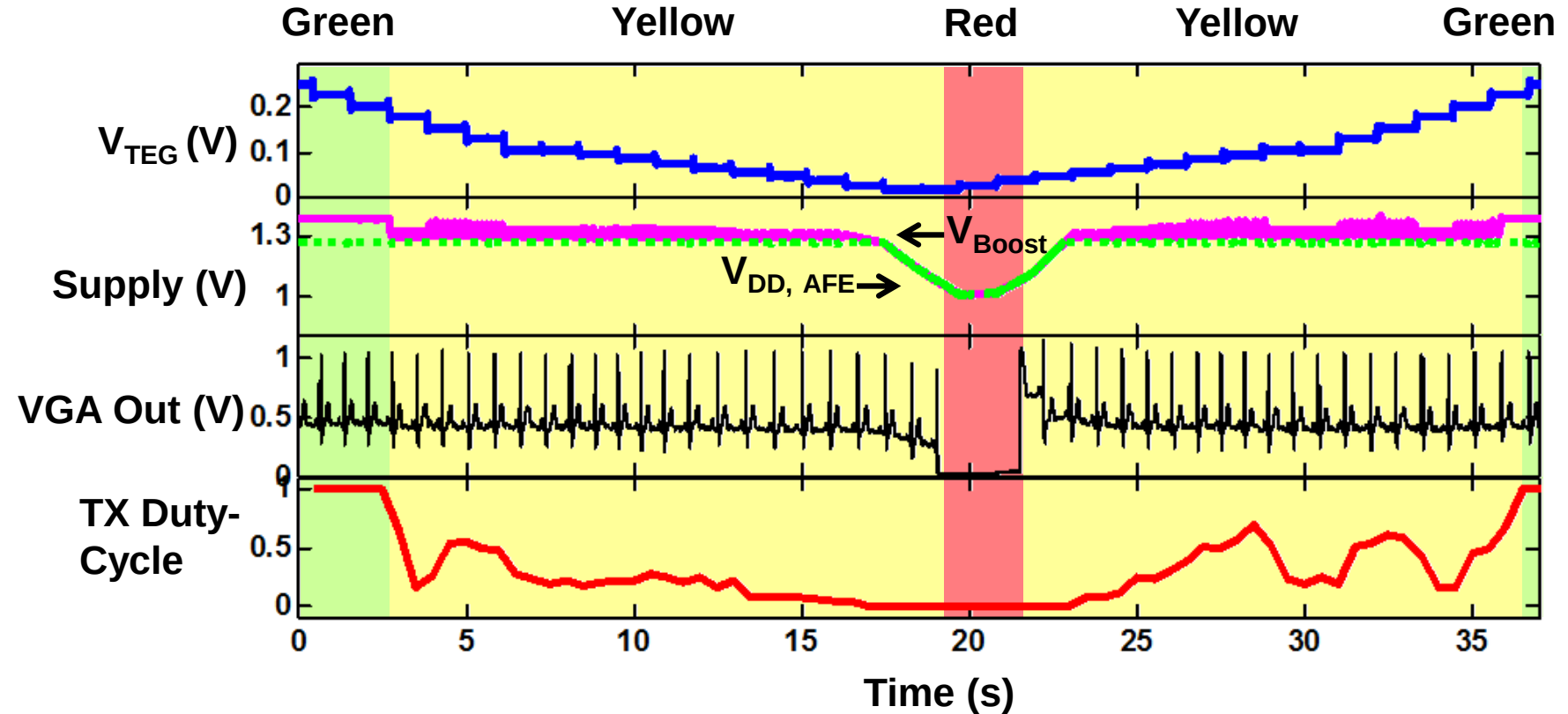
1.2V	PADS, AFE
1.0V	TX LO
0.5V	TX PA
0.5V	DPM, MEM, ACCEL
Variable	0.25-1.0V in 50mV, enabling DVS.

Power management scheme



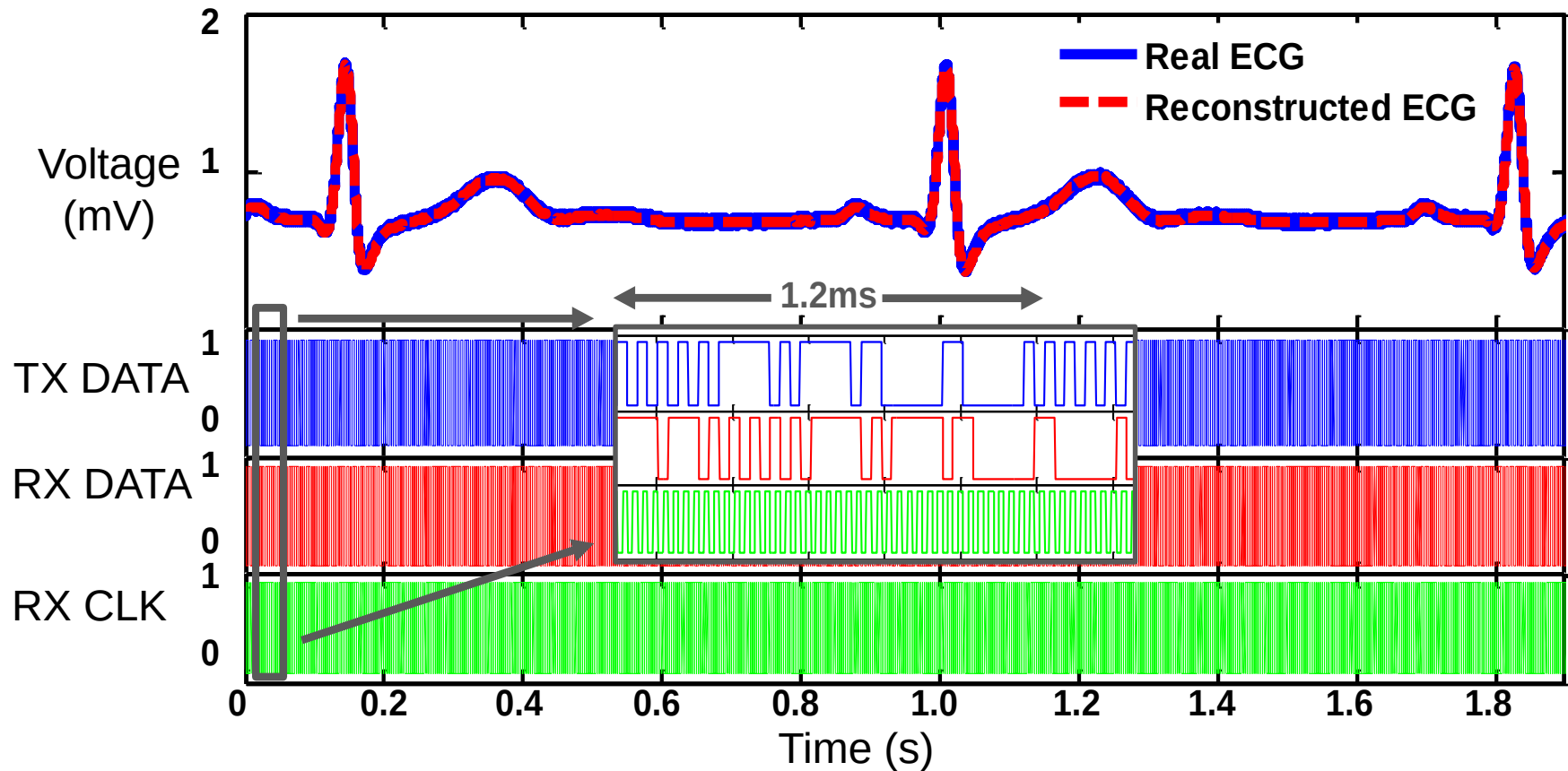
- V_{BOOST} is scaled and digitized
- DPM compares V_{BOOST} vs. V_{THR} (programmable)
- DPM chooses reconfigurable modes (“stoplight”)

Closed-loop power management



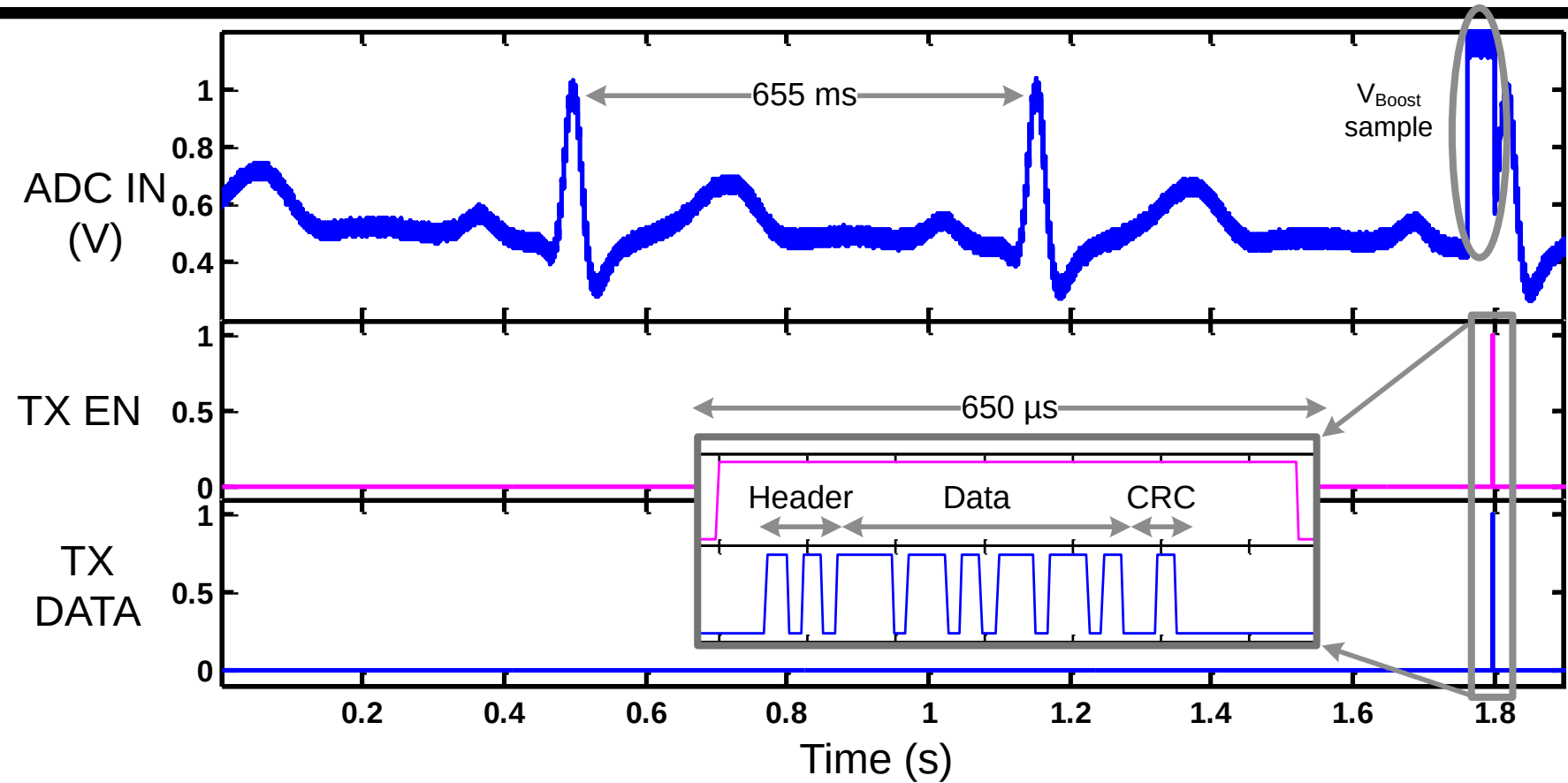
Stoplight	MODES	AFE	Process	Data Mem.	Inst. Mem.	Transmit	V_{THR}
	Green	✓	✓	✓	✓	✓	1.35 V
							1.3 V
	Yellow	✓	✓	✓	✓	x/✓	1.1 V
							0.9 V
	Red	x	x	x	✓	x	

Continuous transmission of ECG



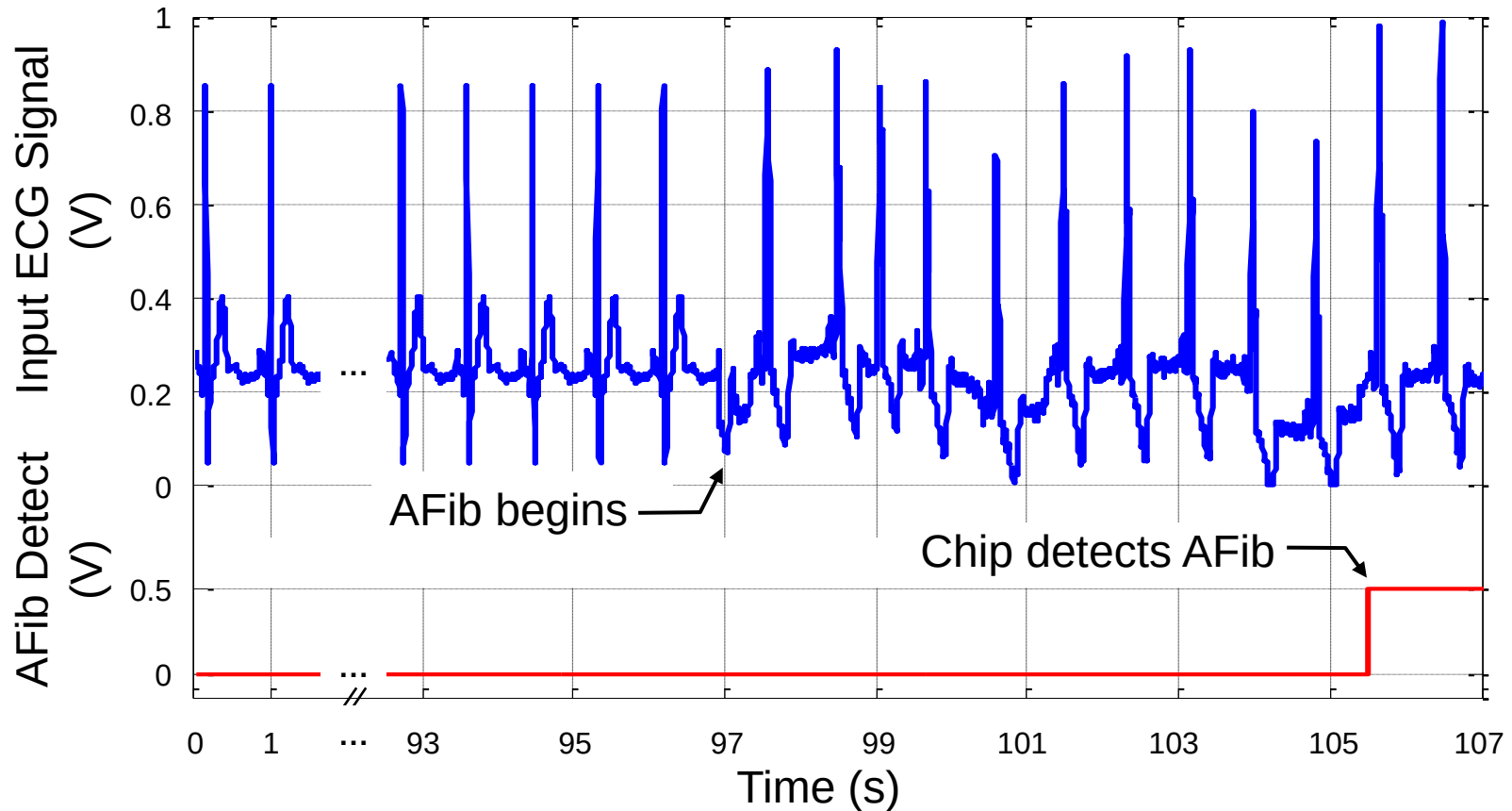
- ECG signal measured from a healthy human subject
- Wireless link demonstrated between the custom IC and a commercial receiver (TI CC1101)
- **397 μW** from V_{BOOST}

R-R interval extraction of ECG



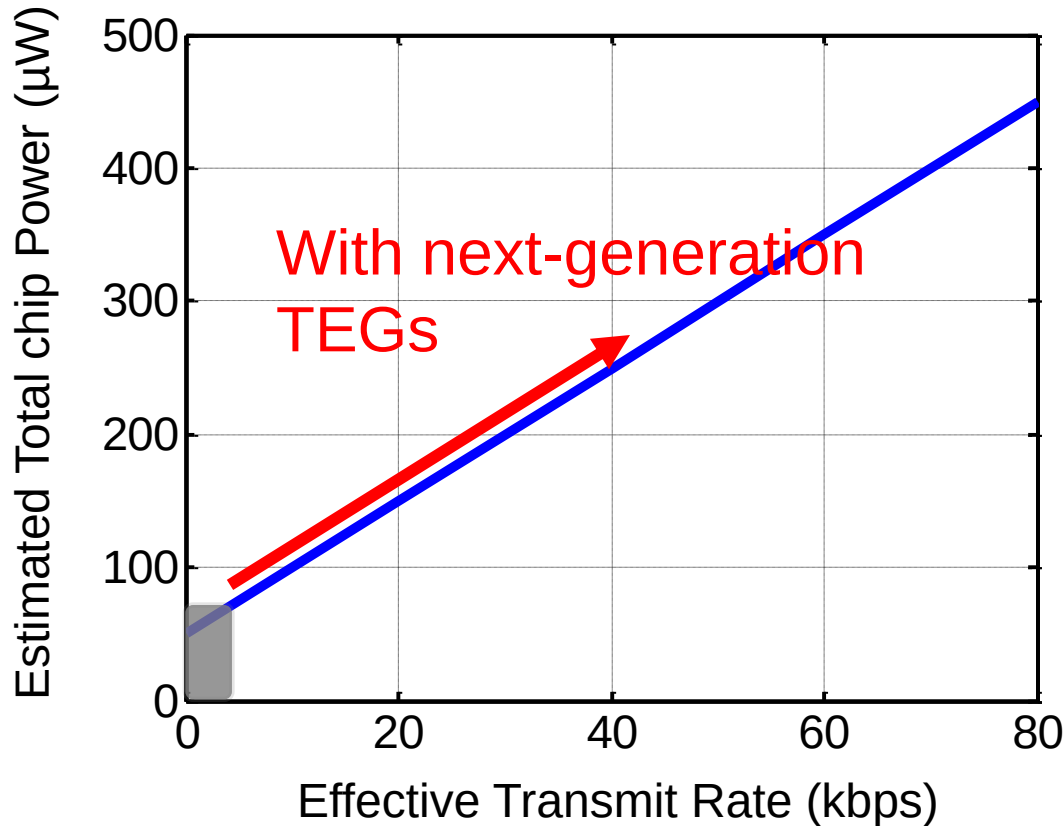
- Every 5s, V_{BOOST} is sampled to check for sufficient energy
- DPM enables RF crystal oscillator (20ms) and TX (650 μ s)
- **19 μ W** from V_{BOOST}
- Powered from a 30mV input

AFib detection of ECG

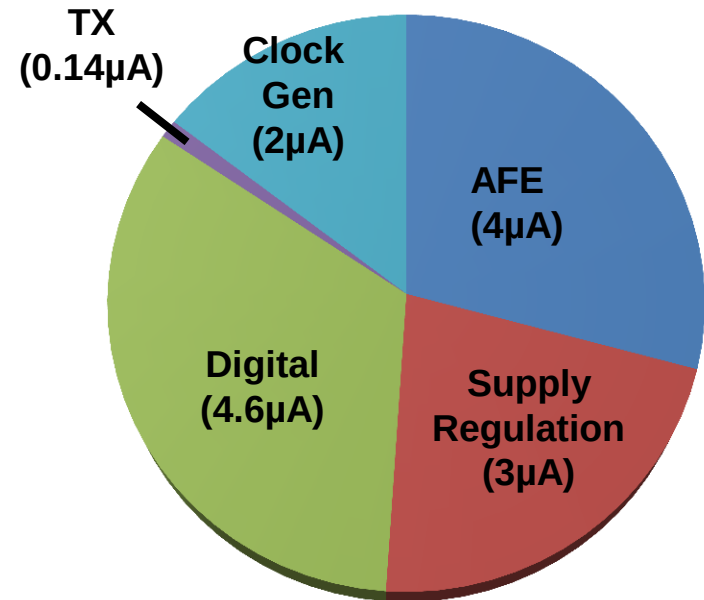


- When a rare AFib occurs, TX is enabled to transmit the last 8 beats of ECG (in the data memory).
- **19 μW** from V_{BOOST}
- Powered from a 30mV input

Selective transmission



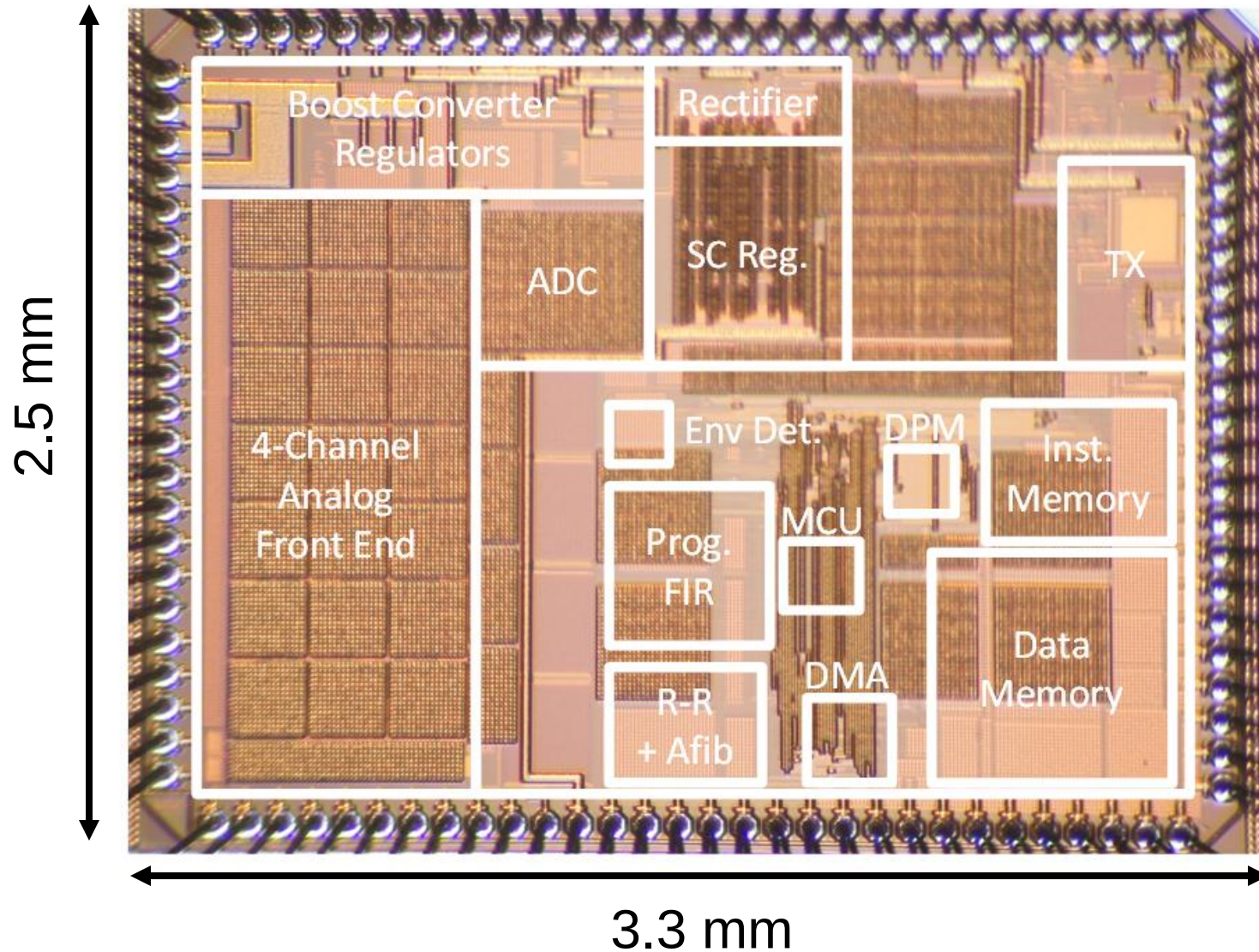
■ Battery-free with TEGs today



- Selective TX and ULP circuits enable energy harvesting

SoC die photo

0.13 μm CMOS



Comparison with prior work

	This Work	Kim VLSI'11	Rai ISSCC'09	Verma JSSC'10	Yan JSSC'11	Chen ISSCC'10
Sensors	ECG, EMG, EEG	ECG	Neural, ECG, EMG, EEG	EEG	ECG, TIV	Temp, Pressure
Supply Voltage	30 mV, -10 dBm	1.2 V	1 V	1 V	1.2 V	0.4/0.5 V
E Harvesting	Thermal, RF	✗	✗	✗	✗	Solar
Supply Reg.	✓	✗	✗	✗	✗	✓
AFE	4-ch	3-ch	1-ch	18-ch	4-ch	N/A
TX datarate	200 kb/s	✗	100 kb/s	✗	1 Mbps (On-body link)	✗
TX P _{DC} (100% on)	160 μ W	✗	400 μ W	✗	2.8 mW	✗
TX P _{OUT}	-18.5 dBm	✗	-16 dBm	✗	-6 dBm	✗
TX band	402 / 433 MHz	✗	402 / 433 MHz	✗	20-40 MHz	✗
Power Mgmt.	Clock + Power gating, DPM	Clock gating	✗	✗	✗	Power gating
DVS	✓	✗	✗	✗	✗	✗

Comparison with prior work (cont.)

	This Work	Kim VLSI'11	Rai ISSCC'09	Verma JSSC'10	Yan JSSC'11	Chen ISSCC'10
Micro-processor	1.5 pJ/Inst 200kHz (8b RISC ISA)	x	x	x	x	28.9 pJ/Inst 73kHz (32b COR-M3)
Accelerator	Prog. FIR, AFIB, DMA, Env. Det., Packetizer	4x SIMD, FIR, DMA, Encryption	x	ASIC DSP	FIR, Packetizer, Compression	x
Memory	5.5kB (0.3-0.7V)	42kB (1.2V)	x	x	20kB (1.2V)	5kB (0.4V)
Dig. Power	2.1μW	~12μW	N/A	2.1μW	500μW	2.1μW (MCU)
Total Power	19μW	31.1μW	500μW	77.1μW	2.4mW	7.7μW
Note on Total Power (includes):	8b ADC, DSP (R-R extract), TX at 0.013% DC	12b ADC, DSP (heart beat detection)	8b ADC, TX at 100% DC	12b ADC, DSP (EEG feature extraction)	10b ADC, DSP (data comp, FIR), SRAM, TX at 5% DC	Data acquisition, DSP (DFT), SRAM
Technology	130nm	180nm	130nm	180nm	180nm	180nm

Conclusion

1. First wireless biosignal processing chip powered solely from a TEG with RF kickstart enabling battery-free operation
2. Our chip integrates state-of-the-art MICS/ISM transmitter, AFE, powertrain, and biosignal accelerators
3. These blocks are intelligently controlled to enable programmable datapath and closed-loop power management

Thank you!